Kingdom of Tonga

Coping with Climate Change in the Pacific Island Region

A Pre-Feasibility Study on Wind Energy for Tongatapu Island, Kingdom of Tonga

October 2012

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

SPC Secretariat of the Pacific Community

german cooperation
DEUTSCHE ZUSAMMENARBEIT

PREFACE

Pacific Island countries (PICs) are among those most vulnerable to climate change impacts, and there is an urgent need to progress adaptation and mitigation measures in the region.

In this context, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the Secretariat of the Pacific Community (SPC) are jointly implementing the regional programme “Coping with Climate Change in the Pacific Island Region” (CCCPIR).

CCCPIR aims to build and strengthen the capacities of Pacific member countries and regional organizations to adapt to, and mitigate, climate change impacts. The programme started in January 2009 and will end in December 2015.

The overall objective of CCCPIR is to strengthen the capacities of regional organizations in the Pacific Islands region and its member states to adapt to climate change and mitigate its causes. To achieve this objective, CCCPIR has six components: 1) strengthening regional advisory and management capacity, 2) mainstreaming climate considerations and adaptation strategies, 3) implementing adaptation and mitigation measures, 4) sustainable tourism and climate change, 5) sustainable energy management and 6) climate change education.

The CCCPIR sustainable energy management component began in January 2012 in six countries: Fiji, Kiribati, Nauru, Tonga, Tuvalu and Vanuatu. Its objective is to strengthen the climate-related services of public and private service providers in the energy sector and improve their focus on sustainability, reliability and cost-effectiveness in the energy sector within the region.

This wind pre-feasibility study is part of the support provided by CCCPIR to the Government of Tonga, through the Energy Division of the Ministry of Environment and Climate Change.

ACKNOWLEDGEMENTS

This report was written by Kevin Palmer-Wilson for the SPC-GIZ Coping with Climate Change in the Pacific Island Region (CCCPIR) programme funded by the Federal Ministry of Economic Cooperation and Development of the Government of Germany.

Ms. Katerina Syngellakis (GIZ Adviser on Sustainable Energy Management) initiated and provided guidance and technical advice for this report.

Mr. William Thorp (SPC Energy Specialist, North Pacific ACP Renewable Energy and Energy Efficiency Project) provided technical advice and comments for the preparation of the report.

The Energy Division of the Ministry of Environment and Climate Change of the Government of Tonga provided the necessary wind measurement data and throughout the work valuable support was provided by Mr. Ofa Sefana, Acting Energy Planning Specialist and his team in the Energy Division.

The Tonga Energy Road Map Implementation Unit (TERM-IU), Tonga Power Limited (TPL), Tonga Meteorological Services and the Tonga Ministry of Lands, Survey, Natural Resources and Environment also provided valuable data for this report.

The work also benefited from the guidance of Mr. Asipeli Palaki, CEO of the Ministry of Environment and Climate Change and the Tonga CCCPIR Steering Committee.

TABLE OF CONTENTS

List of Tables

List of Figures

LIST OF ABBREVIATIONS

C_A	Annual recurring cost [TOP]
C_C	Capital cost [TOP]
C_R	Renaturation cost [TOP]
C_t	Sum of costs in year t [TOP]
Q_t	Sum of revenues in year t [TOP]
€	Euro
AEP	Annual Energy Production
agl	Above Ground Level
AUD	Australian Dollars
CCCPIR	Coping with Climate Change in the Pacific Island Region
CF	Capacity Factor
CF	Capacity Factor
dB	Decibel
DEM	Digital Elevation Model
ESE	East South East
GDP	Gross Domestic Product
GIS	Geographical Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GoT	Government of Tonga
GPS	Global Positioning System
Hz	Hertz
IRR	Internal Rate of Return
J	Joule
K	Kelvin
km	kilometer
km/h	Kilometers per Hour
kWh	Kilo Watt Hour
LCOE	Levelized Cost of Energy
m	Meter
m/s	Meters per Second
MCP	Measure Correlate Predict
MECC	Tonga Ministry of Environment and Climate Change
MW	Mega Watt
MWh	Mega Watt Hour

NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
NZD	New Zealand Dollars
ONI	Oceanic Nino Index
Pa	Pascal
PDF	Probability Density Function
PPA	Power Purchase Agreement
PV	Photovoltaic
SRTM	Shuttle Radio Topography Mission
TMS	Tonga Meteorological Service
TOP	Tonga Pa’anga
USD	United States Dollars
WACC	Weighted Average Cost of Capital
WAsP	Wind Atlas Analysis and Application Programme
WAsP	Wind Atlas Analysis and Application Program
WRA	Wind Resource Assessment
WTG	Wind Turbine Generator
E	Annual net wind energy production [kWh]
P	Air Pressure [Pa]
R	Specific Gas Constant For Dry Air [J/kgK]
T	Air Temperature [K]
n	Project lifetime in years
r	Discount rate
ρ	Air Density [kg/m]

1. EXECUTIVE SUMMARY

The Kingdom of Tonga is an island nation in the South Pacific. As electricity is largely produced from imported diesel fuel, the country has one of the highest electricity tariffs in the world. In an attempt to lessen the impact of oil price increases, the Government of Tonga compiled the *Tonga Energy Road Map 2010 – 2020.* As a part of this long-term strategy, a goal was formulated to produce 50 % of Tonga's electricity from renewable sources by 2012.

Currently, 96 % of electricity on the main island Tongatapu is generated from diesel fuel, while the remaining 4 % is produced by a recently installed 1 MW solar farm. To increase the share of renewable energy and to diversify the mix of fluctuating sources, the Tonga Energy Road Map (TERM) identifies wind power as another potentially viable technology.

Previous wind studies in the region indicate that wind farms in the South Pacific can be implemented at a cost between 3000 USD and 5000 USD per kW of installed capacity. A previous study of the wind resource on Tongatapu has concluded that wind speeds are highest on the eastern side of the island, as well as the north-western peninsula. Since the prevailing wind direction is east, a 50 m tall wind monitoring mast was installed on the central-eastern coast of Tongatapu. The mast meets international standards for wind resource analysis.

After verification and validation of the wind measurement records, data from July 2010 to April 2012 was found to show an annual mean wind speed of 6.6 m/s at 50 m agl. As the time period of this measurement is too short to capture the annual variability of mean wind speed, the data was adjusted to reflect the long-term average by applying the measure-correlate-predict methodology. Here, reference data from the nearby Fua'amotu International Airport was used to show that the measurement period was dominated by below-average wind speeds. Therefore, the long-term adjusted mean wind speed was found to be 6.8 m/s at 50 m agl and all subsequent analyses for this study were based on the long-term adjusted wind resource.

A wind resource map was compiled using the WindPRO software and the WAsP model. Here, a digital elevation model and a digital land cover model of Tongatapu were used to produce a high resolution map with a wind speed interval of 0.2 m/s. By applying this map, high wind speed locations were identified in order to position wind turbine generators appropriately. Although the turbines were placed to render the maximum amount of energy, shadow flicker and noise emissions were taken into account in order to minimize the impact on neighbouring residents.

A 1.1 MW wind farm was designed containing four 275 kW wind turbine generators manufactured by Vergnet SA. The turbine model is suitable for cyclone prone areas such as Tonga, since the tower can be tilted to the ground in order to secure the nacelle in case of extreme wind speeds.

The P50 annual energy production was quantified at 2696 MWh per year which represents 5.8 % of Tongatapu's electricity demand. The capacity factor was calculated at 28 %. It is important to note that these values represent net values. This means that a number of losses such as wake and turbine availability have been accounted for, in order to avoid overestimation of the energy production.

While taking into consideration an estimated 1 % reduction in diesel generator efficiency, the wind farm will enable fuel savings of approximately 560,000 litres of diesel per year. This represents a reduction of approximately 5 % of Tongatapu's diesel fuel used in electricity production.

In order to assess the financial viability of the project, the cost of the wind farm, as well as the value of potential diesel fuel savings were forecasted for the 21 years of project lifetime. Cost projections for the wind farm were based on recent studies conducted in the South Pacific region, estimates and quotations provided by Tonga Power Limited (TPL) and Vergnet. Diesel fuel price projections are based on a 2010 World Bank report compiled for Tongatapu.

The wind farm is estimated to incur a capital cost of 5.63 million TOP which translates to approximately 2,970 USD per kW of installed capacity. Operations and maintenance consume 89,500 TOP annually, while renaturation costs amount to almost 2 million TOP at the end of the lifetime of the wind farm. At a discount rate of 7 %, the levelized cost of energy is 24.6 Seniti per kWh, the net present value is 9.8 million TOP and the internal rate of return is 24.3 %. Cash flow projections show that the wind farm will have paid for itself in diesel fuel savings after six years of operation.

Despite the positive financial indicators, economic advantages and disadvantages need to be taken into account when considering the further pursuit of wind power in Tonga. While some advantages include the reduced dependence on fuel imports, reduced carbon dioxide emissions as well as employment opportunities, a wind farm has a significant impact on the environment. It is therefore important to investigate and present all advantages and disadvantages of this project transparently, in order to make a decision that benefits the Tongan people as a whole.

In conclusion, this report recommends the further investigation of wind power for Tonga as a viable alternative to diesel fuel for electricity generation. The results presented in this study show that financial and economic benefits are significant, and the technology is technically feasible to be implemented on the island. It is therefore recommended to conduct a full feasibility study that shall include the following activities:

1. Validate long-term wind resource
2. Investigate alternate wind farm locations
3. Evaluate the availability of land
4. Evaluate uncertainties to quantify P90 value
5. Model the electrical grid
6. Investigate the need to implement high-speed diesel generators or other suitable energy storage technologies
7. Assess the **environmental impact** assessment
8. Assess geological and topographical conditions
9. Confirm wind turbine suitability for turbulence conditions
10. Adapt wind turbine generator locations to additional assessments
11. Redesign financial models to include additional quotations rather than estimates

2. INTRODUCTION

2.1. Background

The Kingdom of Tonga has some of the highest electricity prices in the world because all grid connected electricity is produced by generators fuelled on imported diesel[1]. The small island nation has no native oil or gas resources and is consequently heavily dependent on fossil fuel imports. Currently, the cost per kWh of electric energy is 0.85 Tonga Pa'anga (TOP), equivalent to 0.49 USD (van Brink, 2012). This high cost puts an enormous burden on this developing nation, where the per capita gross domestic product (GDP) was an estimated 3,518 USD in 2010 (U.S. Department of State, 2011). In comparison, Germany had a per capita GDP of 40,631 USD in the same year, while residential electricity prices are currently around 0.28 USD per kWh (U.S. Department of State, 2011).

As shown in Figure 1, the Kingdom of Tonga is located in the South Pacific, about 2,000 km north east of New Zealand and 3,200 km east of Australia. Tonga comprises 176 islands of which 36 are inhabited (TERM, 2010). The main island Tongatapu holds just over 72,000 people or 71% of Tonga's population. In total, the kingdom had a population of 101,991 counted in the 2006 census with an annual growth of 0.4% (TERM, 2010).

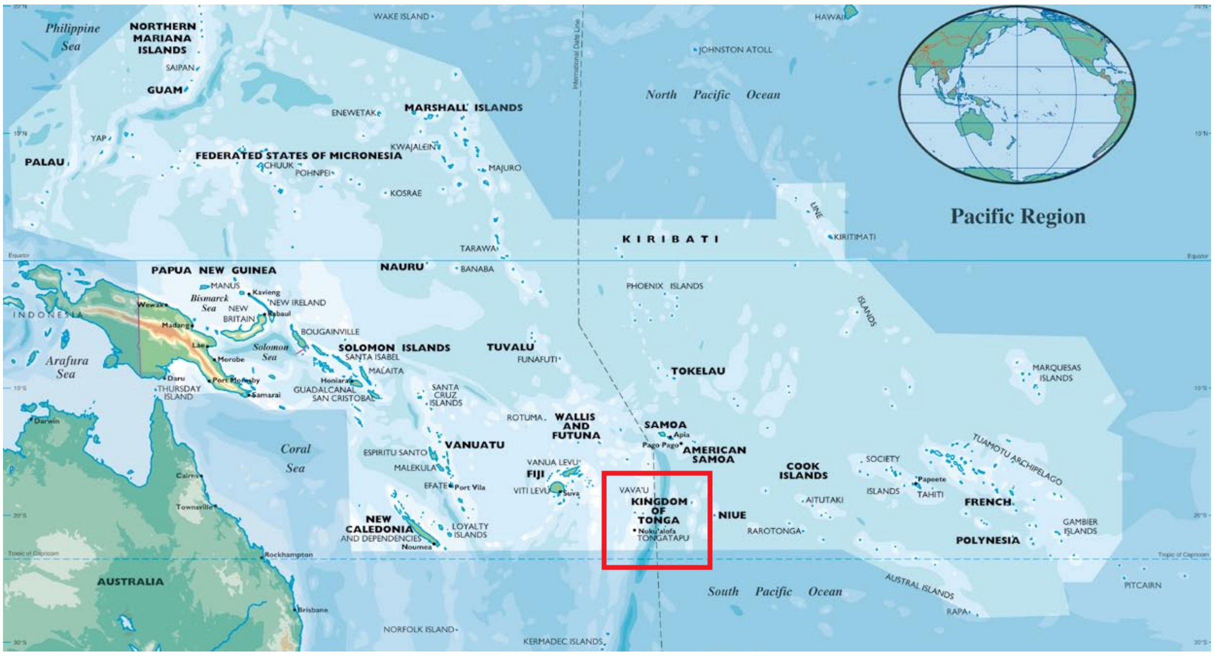


Figure 1 Map of the highlighted South Pacific Region indicating the location of the Kingdom of Tonga in red (SPREP, 2006)

[1] The first grid-connected photovoltaic generator on Tongatapu was commissioned during the undertaking of this study, but it had not been completed when this part of the report was written.

Tonga is highly vulnerable to oil price shocks. With a rather fragile economy, energy price increases are difficult to bear. Since Tonga is a small trading partner in comparison, the country has very little leverage towards international oil companies. Any alteration in price for petroleum products directly affects the welfare level of the Tongan society.

In an attempt to lessen the dependency on oil imports and the adverse effects of oil price increases, the Government of Tonga (GoT) has compiled a comprehensive 10 year strategy known as the *Tonga Energy Road Map 2010 – 2020*. The approach describes and ranks activities for reforming Tonga's energy sector. These include:

- Policy, regulatory, legal and institutional reviews
- Revised petroleum product supply chain management
- Implementation of energy efficiency measures
- Renewable energy implementation goals

The renewable energy implementation goals are ambitious: The target is to produce 50 % of Tonga's electricity from renewable sources by 2012. Since diesel used in electricity production has a share of over 20 % of Tonga's total petroleum imports (TERM, 2010), electricity from renewable sources can significantly reduce fossil fuel dependency. Although the 50% goal will not be reached this year, the strategy clearly reflects the country's will to shift away from fossil fuels.

For the purpose of pursuing a high share in renewables, a consulting firm was given the task to analyze different technological options. The report suggests that implementing photovoltaic electricity generation into the Tongatapu electric grid would be the least-cost alternative for increasing the share of renewable energy in Tonga (GHD Australia, 2010a). Consequently, this technology was the first to be implemented resulting in the 1 MW Popua Solar Farm scheduled to go online by July 2012. This is Tonga's first grid connected renewable energy generator and it will produce 4 % of Tongatapu's electricity demand (Meridian Energy, n.d.).

Second to photovoltaic, wind energy was identified to be the next least-cost alternative (GHD Australia, 2010a). Implementing a wind energy project requires thorough preparation. It is recommended international practice to assess the available wind resource at or close to the proposed wind farm location by installation of a wind monitoring mast. Concurrent with recommendations, the Tongan Ministry of Environment and Climate Change (MECC) has installed a 50 m wind monitoring mast at Lapaha on Tongatapu (see Figure 2). The Lapaha wind monitoring campaign has been operating since July 2010 making crucial data available for the evaluation of the technical and economic feasibility of a wind energy project.

Figure 2 Tonga's main island Tongatapu and the location of the wind monitoring mast (Google Earth, 2012c)

Although an extensive literature review found that some wind resource assessments have been carried out for Tongatapu, an up-to-date wind energy pre-feasibility study is needed. Data used in previous assessments was not of sufficient quality to accurately predict potential energy production (see chapter **Error! Reference source not found.**). Furthermore, many wind energy pre-feasibility studies carried out for other islands in the South Pacific were not up to international standards and of varying depth and quality. Performing an in-depth preliminary assessment of the feasibility of a wind energy project in Tongatapu will allow stakeholders to make an informed decision on whether to pursue this technology.

2.2. Objective of the pre-feasibility study

2.2. Objective of the pre-feasibility study

The objective of this study is the preliminary evaluation of the technical and the economic feasibility of a wind farm on Tongatapu Island in the Kingdom of Tonga. As both evaluations are mainly influenced by the available wind resource, a state-of-the-art wind resource assessment is an essential first step. The production of a wind resource map will aid in the selection of suitable wind turbine locations and the potential energy production of a wind farm will be modeled and optimized. When the technical feasibility at a selected site has been confirmed, the economic feasibility study will estimate the cost at which a kWh of electric energy can be produced by the proposed wind farm. Indicative costs for the entire project will be presented. Finally, recommendations on where, how and if a wind energy project should be implemented on Tongatapu Island will be provided.

The study will not only take technical and economic considerations into account. Some important environmental impacts like noise, shadow flicker and reduction of carbon dioxide emissions will also be evaluated and quantified. Options for limiting the environmental impact of a wind energy project need to be discussed and incorporated into the analysis. A full environmental impact assessment will however not be carried out within the scope of research.

In summary, the proposed study will consist of the following parts in an attempt to answer the respective questions:

- Wind Resource Assessment — Is the wind resource suitable for a wind energy project in Tongatapu Island?
- Technical Feasibility Assessment — What would be an appropriate layout and technical configuration for a wind farm on Tongatapu?
- Economic Feasibility Assessment — Is it economically viable to implement a wind energy project in Tongatapu Island?

3. REVIEW OF REGIONAL WIND ENERGY ASSESSMENTS

An extensive literature review has been carried out, focusing mainly on analysis of wind energy pre-feasibility studies from the South Pacific region. The reason for limiting the scope to this area is that conducting business and research in this part of the world differs from e.g. Europe or North America. Naturally, only research aimed at the South Pacific takes region-specific constraints into account. Restrictions like weather phenomena, transportation cost or equipment availability can diverge significantly from conditions found in other parts of the world. Wind energy feasibility studies from regions other than the South Pacific were therefore not reviewed.

Within the analyzed studies, the depth of research, the tasks performed, the data quality used and the adherence to international standards varied greatly. While some studies address only the resource assessment, other researchers merely touched upon the technical and economic assessments. Only few documents were found where all three aspects of a pre-feasibility study were thoroughly examined.

Furthermore, the terms “Wind Resource Assessment” and “Feasibility Study” are not clearly differentiated and therefore used in different contexts by different authors. For the purpose of this study, a wind resource assessment will be defined as an assessment of the wind resource only, where technical and economic constraints are neglected. A preliminary wind energy feasibility study (or wind energy pre-feasibility study) will be defined as an analysis that uses a wind resource assessment to determine if technical constraints allow the implementation of wind turbine generators and if this implementation is an economically viable and cost effective decision.

A full feasibility study goes beyond the scope defined above and would therefore include for example:

- A more detailed technical analysis (e.g. dynamic model of electrical grid)
- A more detailed economic analysis (e.g. based on quotations from contractors rather than estimates)
- An environmental impact assessment
- Considerations of social impacts
- Legal constraints
- Assessment of availability of land.

As not all items will be covered within the scope of this study, this work will be considered a wind energy pre-feasibility study.

3.1. Wind resource assessments in the South Pacific region

A regional wind resource assessment was carried out for Papua New Guinea, the Solomon Islands, Vanuatu and the Fiji Islands (AWS Truewind, 2009). Here, Fiji was shown to have the highest mean wind speeds of up to 7 m/s at 25 m agl, whereas the Solomon Islands had the lowest mean wind speeds of only 4 m/s at 25 m agl. The report confirms that the wind speeds are highest where land is exposed to southeastern winds. It is important to note that this assessment is also based on wind data compiled from a number of sources such as reanalysis and meteorological station data. As no data measured on site at relevant heights was used, the values have to be treated as indicative only.

A number of wind resource assessments have however been carried out using on-site measured data. In Samoa mean wind speeds of 4 m/s where found at 30 m agl while the prevailing wind direction was ESE (GHD Australia, 2010b). The wind data was measured at a height of 30 m agl from Nov 2006 to Nov 2008. In Nauru 4.22 m/s were found at 30 m agl (Factor 4 Energy Projects GmbH, 2010) which was measured at 30 m from July 2009 to June 2010. In Niue a measurement from October 1994 to February 1997 yielded a very high mean wind speed of 5.9 m/s at only 10 m agl (Garrad Hassan Pacific Pty Ltd, 2007). Similarly, a fairly high wind speed of 5.79 m/s was measured at 29.2 m agl in Tuvalu (Ecology Management Aps, 2010). Finally, an assessment of a site in the Cook Islands rendered high wind speeds of 7.2 m/s at 50 m agl.

The wind resource assessments examined in the previous paragraph show that there are substantial differences in mean wind speeds from country to country, but easterly winds are always prevailing. Most assessments analyze wind speeds at heights above ground that are below relevant wind turbine hub heights. A more detailed analysis of wind speeds at hub height is therefore required to implement a wind energy project successfully.

Some utility scale wind energy projects have already been implemented around the South Pacific region. New Caledonia has several wind farms in operation and Vanuatu now has 3 MW in place. Fiji has been operating the 10 MW Butoni wind farm since 2007. Although the wind resource assessment for this project was not available for review, sources state that the mean wind speed should have been 5.47 m/s, but were as low as 4.96 m/s in the first year (Karan, 2009). This forecast was “based on two years wind measurements at hub height at the wind farm site” (PIEPSAP, 2006). Nevertheless, “insufficient study of the area” lead to a capacity factor of only 5.2 % in the first year which is significantly lower than the anticipated 12 % (Karan, 2009). Although this value increased to 7.3 % in 2010 (FEA, n.d.), energy output still fell significantly short of expectations. This incident shows the necessity of performing a reliable wind resource assessment which uses accurate wind speed data.

3.2. Wind resource assessments in the Kingdom of Tonga

The Kingdom of Tonga has been considering the use of wind energy technologies at least since the mid 1990s. The first wind speed measurements were conducted on Tongatapu as early as 1995 and 1996. Average wind speeds at 10 m above ground level (agl) were 4.38 m/s and 4.26 m/s respectively (Enviromet Meteorological Consultants, 1997).

Another assessment was carried out using wind data measured from November 1999 to October 2000 at 20 m agl. The study found that the mean wind speed during that period was 4.8 m/s at 20 m agl and concluded that "it is impossible to construct a wind power plant if the plant ever seeks to gain profit" (Electric Power Development Company, 2001). As utility scale wind turbines have hub heights well beyond 10 m, other consultants recommend an "assessment […] at 30-50 meter heights […] to better understand the wind regimes that can actually be tapped for energy" (Wade, 2005).

In 2007 mean wind speeds at 30 m and 50 m agl were assessed and a wind resource map of Tongatapu was created for the respective heights (see Figure 3).The report states that the prevailing wind direction is East South East (ESE) (Vergnet Pacific, 2007). As a result of this, the wind resource map shows that mean wind speeds are significantly higher on the eastern side of Tongatapu. This characteristic was found in all South Pacific wind resource assessments that were reviewed for the purpose of this study.

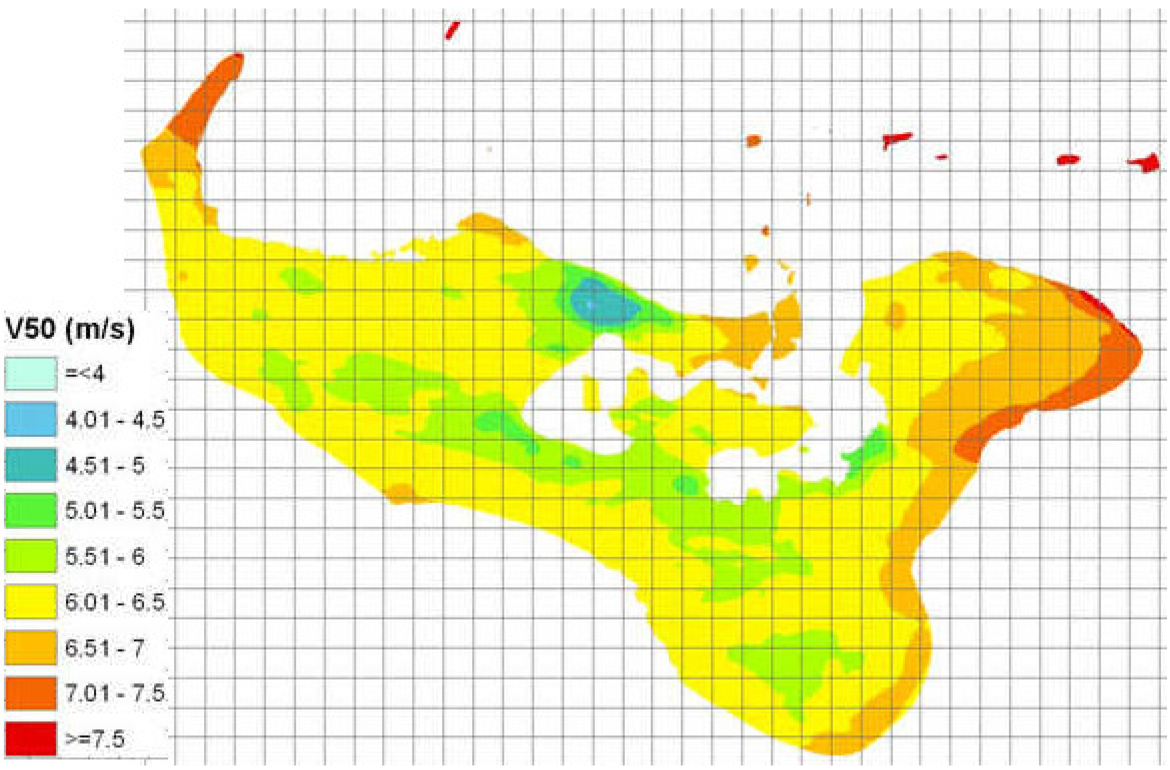


Figure 3 Wind resource map of Tongatapu at a height of 50 m agl (Vergnet Pacific, 2007)

The calculations were however based on the Winergy wind database, not on direct measurements (Vergnet Pacific, 2007). The authors claim that the data is accurate and verified because it incorporates inputs from satellite measurements, reanalysis data and meteorological station measurements. The database however generates a vector field of wind data at 10 m agl with a grid point spacing of 1° (approximately 100 km). Therefore, the wind data used in this assessment was generated for a grid point about 15 km off the shore of Tongatapu and extrapolated from 10 m to 50 m agl. The wind speeds predicted in this study can therefore only be seen as indicative. Hence, research based on more accurate measured wind data from actual wind monitoring masts with relevant height (i.e. 50 m agl) on Tongatapu is necessary for the implementation of a wind energy project.

3.3. Technical feasibility of wind energy projects

When integrating wind turbine generators into a relatively small electrical grid, the maximum power output of that project needs to be chosen carefully. In order to accommodate all the electricity produced in times of high wind speeds but low consumer demand, the rated power of the wind farm needs to be less than the lowest consumer demand (if no storage is present). On the other hand, maximizing diesel savings implies choosing a power output that is as large as possible.

The electric load in Tongatapu ranges from approximately 3200 kW to 8200 kW (World Bank, 2010). The maximum feasible wind energy penetration for Tongatapu has been investigated in a 2010 study which concluded that the maximum wind power may be no more than 1000 kW (GHD Australia, 2010a). The model takes the presence of a (yet to be built) 2100 kW photovoltaic generator into account, as well as the fact that diesel generators may not be operated under their minimum power output rating. Since energy output from a wind turbine fluctuates significantly, a (diesel) generator must supply the remaining load at all times.

A major concern in the South Pacific is the occurrence of tropical cyclones. In March 2003 cyclone Erica hit New Caledonia’s Plum Wind Farm with wind gusts above 200 km/h. Here, Vestas had previously installed 20 x 225 kW generators on 32 meter lattice towers. 10 turbines suffered damage and 5 were destroyed, resulting in damages amounting to approximately 50 % of the initial investment (GHD Australia, 2010a). The nearby Col de Prony Wind Farm had 10 x 220 kW Vergnet turbines installed on tiltable towers. “These generators were lowered during Erica and suffered a damage of 2 % of the initial capital investment.” (PIEPSAP, 2006). This incident implies that taking cyclones into account is crucial when selecting the wind turbine to be installed.

Figure 4 Cyclone damage to Vestas turbines at Plum Wind Farm in 2003 (PIEPSAP, 2006)

Like Tongatapu, most electrical grids in the South Pacific are simply not large enough to accommodate wind turbines in the megawatt range. An extensive study conducted in 2007 found that only 8 wind turbine manufacturers supply turbines in the range from 80 kW to 300 kW (PIEPSAP, 2007). These turbines are potentially suitable for a utility scale wind farm in Tonga, but a 2009 pre-feasibility study found that no turbine manufacturer other than Vergnet was willing to supply their equipment to the South Pacific (GHD Australia, 2010b). Therefore, Vergnet wind turbine generators will be used for the design of a wind farm within this study.

3.4. Economic feasibility of wind energy projects

As feed-in-tariffs for wind energy are typically not available in the South Pacific, the economic feasibility of a wind farm in Tonga mainly depends on the capital cost of the turbines in comparison to the price of the diesel fuel that is being saved. In order to assess the benefit of wind energy, the cost per kWh produced by a wind farm needs to be compared to the cost per kWh produced by an alternate source. In Tonga's case the alternate source is a diesel generator. If the cost of wind energy is cheaper than the cost of diesel fueled energy, then the project is feasible in financial terms.

A utility must always provide enough capacity to supply the highest peak load that may potentially occur. Keeping the generation capacity in stock for this rare peak event is rather costly. One report suggests that apart from taking only the saved fuel into account, a utility may lower its diesel generation capacity and give the wind farm a capacity credit to render extra savings (Cheatham & Zieroth, 2002). Another author states that since no conventional power plant is safe from unexpected failure, there is always a risk of not meeting consumer demand. A wind farm has a certain probability of supplying excess consumer demand in case a diesel generator has an unexpected failure. This characteristic adds extra value to a wind farm (Ackermann, 2005). A third assessment however rules out any capacity credit of intermittent renewable energy technologies (GHD Australia, 2010a).

The capital cost of a wind farm is relatively high in comparison to that of a diesel generator. Therefore, this item has a significant impact on the economic feasibility of a wind energy project. Nevertheless, capital cost estimates vary significantly within the reviewed literature (see Table 1). Due to the remoteness of island nations in the South Pacific, transportation costs and therefore installation costs for wind farms are expected to be higher than in the U.S.A. or Europe.

Table 1 Comparison of capital cost for wind farms in the South Pacific

Country	Project Size	Capital Cost per kW [respective currency/kW]	Capital Cost per kW [USD/kW]*	Cost per kWh [USD/kWh]*	Source and Year
Samoa	2 MW	2386 €/kW	**3000**	0.14	(GHD Australia, 2010b).
Niue	275 kW	2665 NZD/kW**	**2072****	-	(Garrad Hassan Pacific Pty Ltd, 2007)
Cook Islands	2 MW	5090 NZD/kW	**3957**	-	(PIEPSAP, 2006)
Cook Islands	3.75 MW	5470 NZD/kW	**4263**	0.36***	(Cheatham & Zieroth, 2002)
Cook Islands	1.8 MW	4768 NZD/kW	**3716**	-	(Cheatham & Zieroth, 2002)
New Caledonia****	4.5 MW	4971 NZD/kW	**3874**	-	(Cheatham & Zieroth, 2002)
Tuvalu	200 kW	3500 – 4500 AUD/kW	**3485 - 4481**	-	(Ecology Management Aps, 2010)
Vanuatu****	3025 kW	1891 €/kW	**2321**	-	(Nouvel, 2012)
South Pacific	-	-	**5000**	0.15 – 0.30	(Wilkenfeld, 2012)

*currency conversion via Google on 14.06.2012

**price per turbine ex works: installation and transport not included

***Price proposed in Power Purchase Agreement (PPA)

****completed project (actual project cost is stated)

While large scale European wind farm cost between 1850 USD to 2100 USD (IRENA, 2012), Table 1 shows that costs in the South Pacific region are significantly higher. It is important to note that these assessments analyze different countries within the South Pacific so prices may vary. Generally, a cost per kW between 3000 USD and 5000 USD can be assumed a realistic estimate in this region. An economically feasible wind energy project will therefore have to displace a diesel fuel consumption that justifies these high capital costs.

4. WIND RESOURCE ASSESSMENT

4.1. Wind data measurement

Assessing the wind resource accurately is crucial because the results are used in many processes throughout the planning of the wind farm. Whether selecting the turbine location, planning grid integration, selecting a wind turbine generator or preparing the financial model, the wind resource largely influences the outcome. A precise assessment of the wind resource in Tongatapu can only be done by carefully analyzing measured wind data that has been collected on the island and close to the hub-height of future wind turbine generators.

For wind data to be suitable for a wind resource assessment a measurement campaign is undertaken to collect wind data for a period exceeding one year. This ensures that seasonal variability is reflected within the measurements (EWEA, 2009). Typically, wind speeds at different heights above ground are recorded during a wind measurement campaign. This allows the calculation of the wind shear factor needed for extrapolating wind speeds to higher levels. Apart from the wind speed, other recorded values should include wind direction and air temperature. While wind direction is crucial for wind park design, the air temperature is used in data validation and turbine selection.

As will be shown below, however, the most important value to be recorded during the measurement is the wind speed. Wind turbine generators extract kinetic energy from moving air masses. The power that can be extracted from the wind is defined by equation 4.1 (Ackermann, 2005). Since wind speed influences the power output as a cubed factor, the amount of power that can be extracted by a turbine is multiplied by a factor of 8 when the wind speed doubles.

$$P = \frac{1}{2}\rho A V^3 C_P \qquad 4.1$$

$P =$ Power (W)
$\rho =$ Air density (kg m^{-3})
$A =$ Swept rotor area (m^2)
$V =$ Wind speed (m s^{-1})
$C_P =$ Coefficient of power

Typically, a wind monitoring mast is used to collect wind data at the required heights above ground. It is important to conduct the measurement campaign in accordance with international standards, in order to ensure that data records are of high quality and therefore acceptable to all stakeholders of the wind energy project.

4.1.1. The Lapaha wind monitoring mast

The wind data used in this resource assessment was kindly provided by the Ministry of Environment and Climate Change of the Government of Tonga. The data was recorded using a wind monitoring mast located close to Lapaha on the eastern coast of Tongatapu Island (see Figure 2). The mast installation was contracted to Clay Engineering Ltd. who documented the set-up. This document has been provided and will therefore be used to assess the installation against international standards.

The mast holds 6 cup-anemometers, 2 wind vanes and 1 thermometer (see Figure 5). Two anemometers per level record wind speeds at heights of 30 m, 40 m and 50 m above ground. The use of cup-anemometers is common practice in wind monitoring (International Energy Agency, 1999).

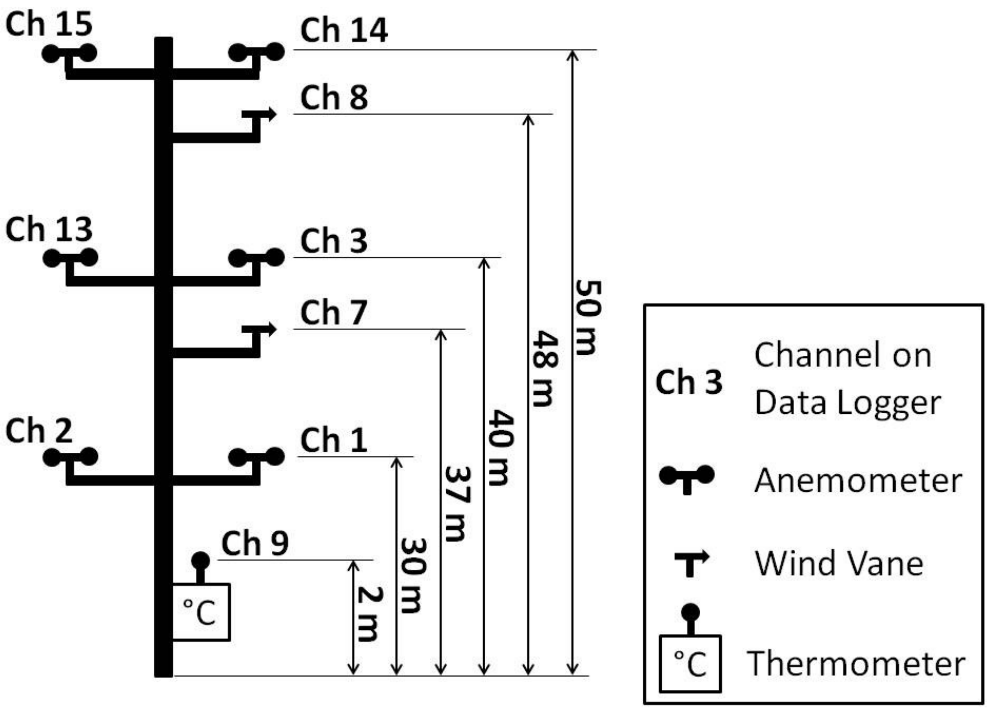


Figure 5 Setup of sensors mounted on the Lapaha wind monitoring mast

Each sensor is connected to the *NRG Symphonie PLUS* data logger (see Figure 6). The device records average values for each 10-minute period. This interval is deemed appropriate for a wind resource assessment (International Energy Agency, 1999). Detailed information on sensors mounted onto the mast is listed in Appendix 1.

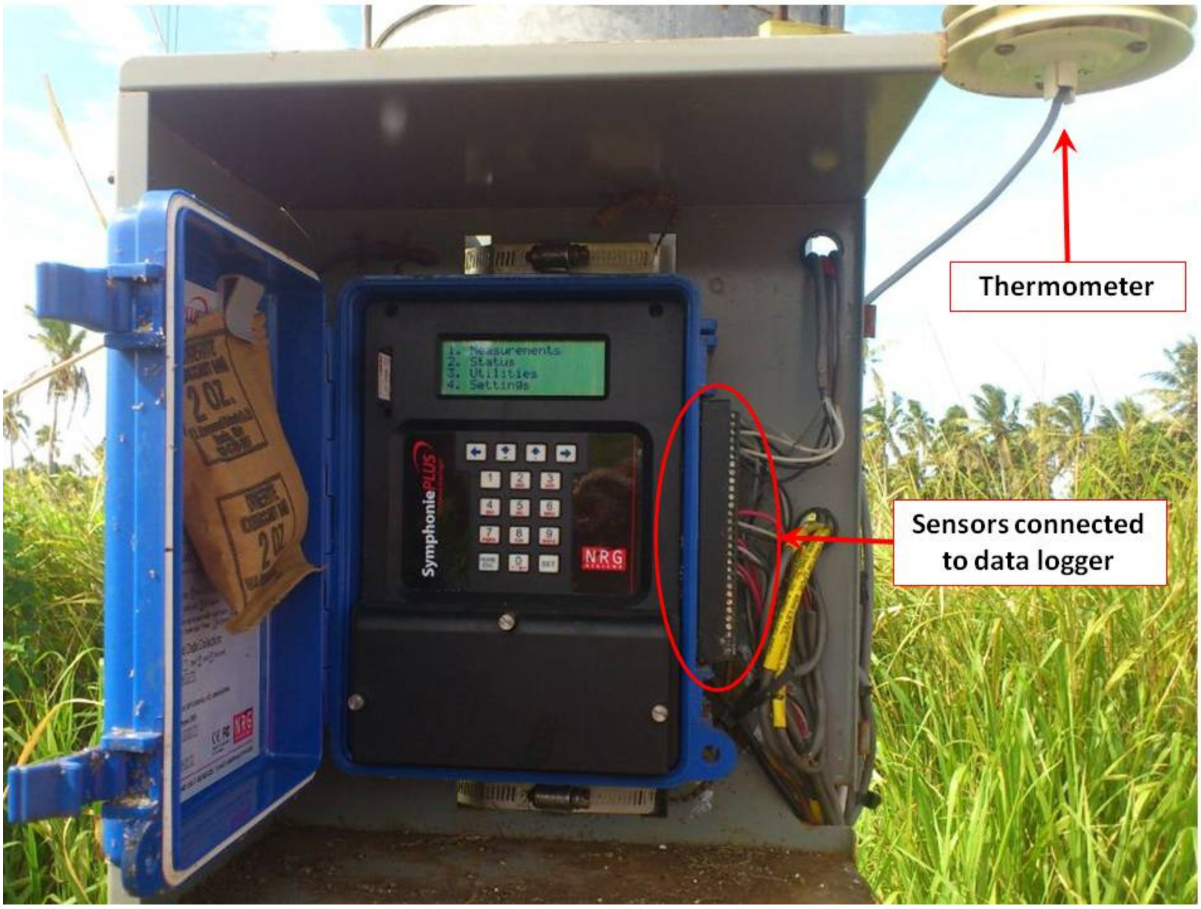


Figure 6 Photo of the *NRG Symphonie PLUS* data logger mounted to the wind monitoring mast

The anemometers and the wind vanes are mounted onto booms to ensure the space between the mast and the sensors is sufficient to minimize the influence of the mast on the air flow. "An anemometer operating in the wake of the meteorological mast is highly disturbed." (IEC, 2005). The standard recommends using a boom length measured from the center of the mast of at least *6.1 x Mast Diameter* to ensure that air flow distortions are minimized to an acceptable level of uncertainty. This requirement is met because the wind monitoring mast is designed specifically for wind resource measurements. While the mast has a maximum diameter of 0.254 m, the boom holds its sensor 2.54 m or *10 x Mast Diameter* away from the centerline of the mast (NRG Systems Inc, 2011). The photo depicted in Figure 7 confirms that booms place sensors well away from the mast.

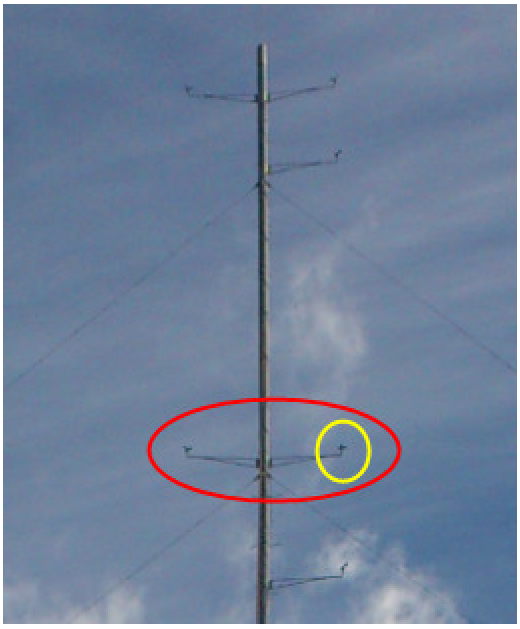


Figure 7 Photo of wind mast highlighting one of the booms and the anemometer at the end of the boom

Not only the length, but also the direction of the booms is an important factor that can influence air flow distortions. As shown in Figure 8 the "least disturbance can be seen to occur if facing the wind at 45°." (IEC, 2005). The booms should therefore be directed at a 45° angle to the prevailing wind direction. This minimizes over- and underestimation of the wind resource.

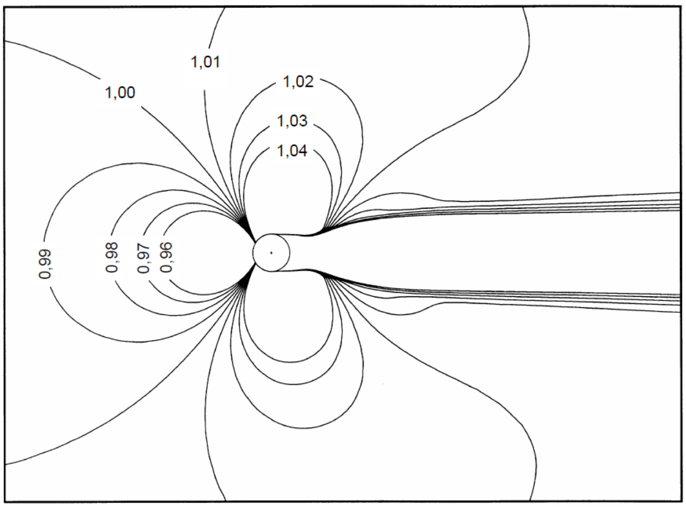


Figure 8 Iso-speed plot of local flow speed around a cylindrical mast, normalized by free-field wind speed coming from the left (IEC, 2005)

As shown in Figure 9 the booms are directed towards 22.5° (in comparison to true north) and 202.5° respectively. Since the literature review concluded that the prevailing wind direction is east, the anemometers and wind vanes facing 22.5° are located in an area of low air flow distortions. The resource assessment will therefore focus on the anemometers on channels 1, 2 and 14 and view the anemometers on channels 2, 13 and 15 as secondary sensors.

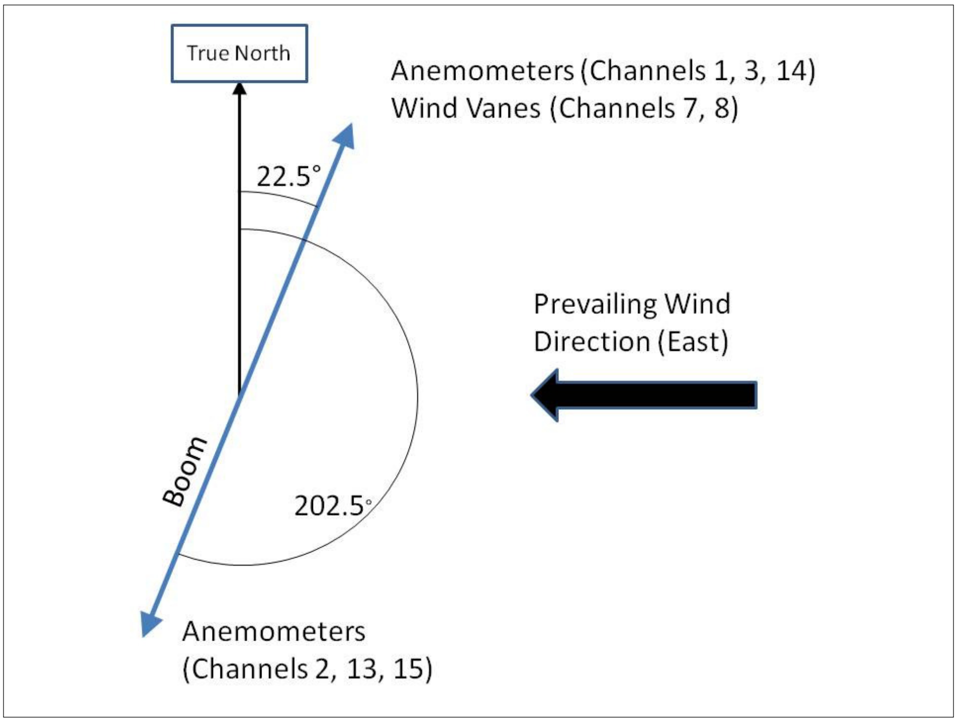


Figure 9 Top-down view of the booms placing the main anemometers and wind vanes in an area of low air flow distortion

Since wind speeds have such a large influence on power production, anemometers must be calibrated in order to minimize the measurement's uncertainty. Therefore, "each instrument must have its own specific calibration certificate" (International Energy Agency, 1999). Comparing the calibration information of each wind speed sensor with those values stored within the data logger is necessary to ensure that the electronic signals are converted to the correct wind speeds.

Copies of anemometer calibration reports can be retrieved from the wind monitoring mast's manufacturer *NRG Systems, Inc*. The reports of all six installed anemometers were downloaded from the company's website (see Appendix 2 to Appendix 7). This step required providing the serial number of each sensor as listed in Appendix 1. Once all calibration reports had been collected, the validity of calibration information stored in the data logger was checked as described below.

Appendix 8 shows a sample of header information stored in each raw wind data file produced by the data logger. This information allows the user to identify which parameters the logger applied to convert the electrical signals into wind speeds. The mathematical procedure behind this operation is a linear transfer function, which is characterized by the Scale Factor and the Offset value. As shown in the calibration report of the channel 14 anemometer (see Appendix 6), the values characterizing the behavior of this sensor are 0.756 and 0.39 m/s respectively. Since these values match the information stored in the data logger (see Appendix 8) the electronic signals of this anemometer are correctly converted to wind speeds. Comparing the calibration values of all anemometers confirmed that parameters stored in the data logger match those listed in the calibration reports. Therefore, the wind speeds recorded by the data logger correctly reflect the wind speeds measured by the anemometers.

In conclusion, the wind monitoring mast meets international standards and the data recorded by the mast is deemed suitable to be used in a dependable wind resource assessment.

4.1.2. Lapaha wind mast data validation

For the purpose of this study the Tongan Ministry of Environment and Climate Change provided wind data recorded by the Lapaha wind mast. The data covers a period of 22 months from *23 Jul 2010 to 31 May 2012.*

Before measured wind data can be used in any calculations, the raw data must be reviewed and validated. A wind measurement campaign can contain many sources of errors such as equipment failure, loss of power, extreme weather conditions etc. Suspect, erroneous and missing data must be excluded from further analysis. This ensures that the wind data represents an accurate sample which in turn allows predictions of future wind regimes.

The data is checked by displaying the values graphically and manually reviewing the measurements of each day. The graphical review is performed in EMD WindPRO, while any correction or deletion is performed within Microsoft Excel. This procedure allows using a "cleaned" dataset in the further resource assessment. A detailed list of all alterations made to the raw wind data can be found in Appendix 9, but the actions will be explained in the following paragraphs.

The data logger began collecting data on 22 July 2010, but the sensors were not yet connected to the logger. Useful data is only collected on 23 July 2010 when the anemometers, wind vanes and thermometer were wired to the logger. This is normal procedure, because the logger is usually programmed in an office where a computer is available. After the device has been programmed, the logger is transported to the field and mounted onto the mast. Once all sensors are connected, useful data is recorded.

Reviewing the timestamp at which useful records are recorded reveals that the internal clock of the data logger had been set to the wrong time. Depicting the data graphically shows that useful records begin at midnight between the 22 and 23 July (see Figure 10). Not only is it highly unlikely that the installer was working at night, also the installation documentation states that the mast was commissioned on 23 July at 2 PM (Clay, 2010).

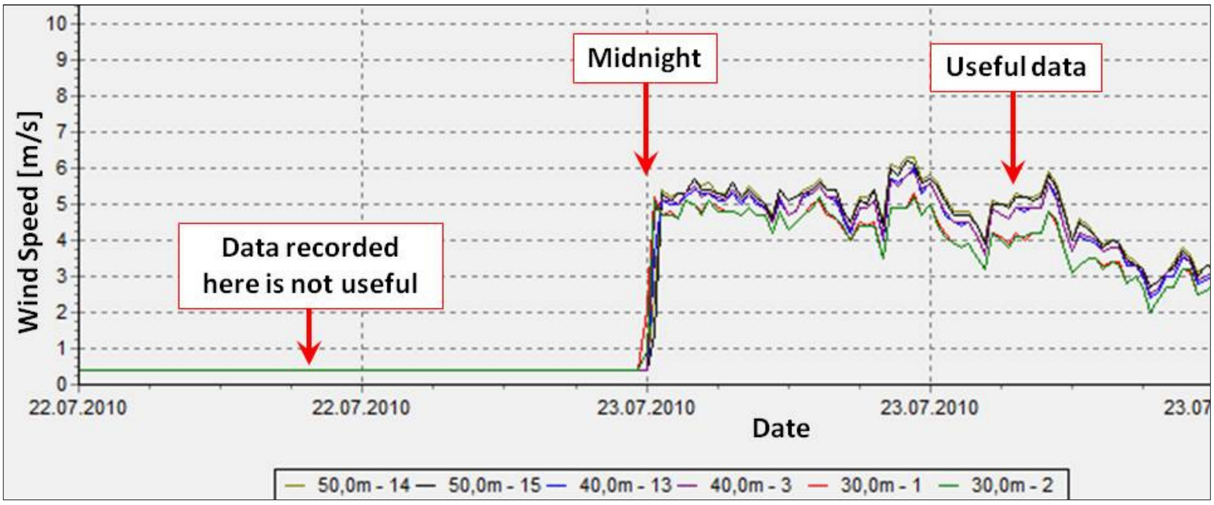


Figure 10 Wind speed measurements on the first day of useful data records

The theory of a wrong time set in the data logger was confirmed during the site visit. Nearly two years after the commissioning of the wind mast, a picture of the logger display was taken at 11:51 AM on 31 May 2012 (see Figure 11). Clearly, the logger is offset by 12 hours[2]. This error can have a significant impact when comparing the data collected from Lapaha to reference data. In response to these findings, 12 hours were added to all timestamps in the dataset at hand.

[2] During the site visit the internal clock of the logger was set to the correct time: All timestamps starting from 31 May 2012 11:50 AM will therefore reflect the correct time.

Figure 11 Photo of data logger display at 11:51 AM on 31 May 2012 proving an offset of 12 hours

The non-useful data at the beginning of the measurement campaign can distort the results. When the logger is active but receives no signal, the logger records the offset value of the sensors at approx. 0.4 m/s. This is caused by the design of the anemometer. The offset value is that wind speed at which an anemometer starts rotating. Therefore, this value is always added to the measured value to receive the real wind speed. If the measured value is 0 m/s because no sensor is present, then the recorded value is 0 + 0.4 m/s. Using these false values in calculations would result in underestimating the wind resource. Hence, all data prior to the connection of the sensors was deleted from the dataset.

When reviewing raw wind speed data, it is crucial to check for sensor failures. When all anemometers are operating normally, they all measure roughly the same wind speed. Anemometers at higher heights (i.e. 50 m agl) measure a slightly higher wind speed, while sensors at lower heights (i.e. 40 m and 30 m agl) measure a slightly lower wind speed. This makes it easy to spot the failure of an anemometer, because its measurement will suddenly diverge from the average path of the remaining sensors.

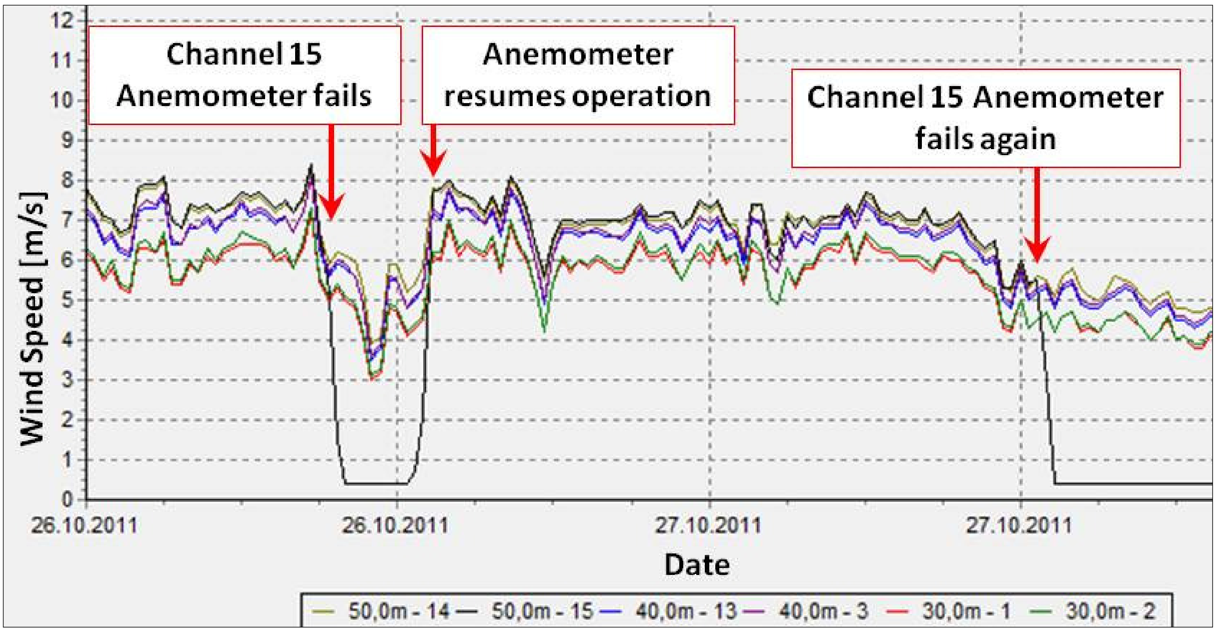


Figure 12 Wind speeds of all six anemometers show that a repeat failure of the channel 15 anemometer occurs

Starting in May 2011, only 10 months after the commissioning of the wind monitoring mast, the anemometer connected to channel 15 starts failing and measurements drop to the offset value (see Figure 12). After a short period of time the anemometer resumes its normal operation and recorded values go back to plausible levels. This phenomenon repeats itself and gets worse as time progresses. Towards the end of the available data, almost all measurements from channel 15 were faulty. All faulty data from channel 15 was deleted.

The cause of this failure might be a loose cable connection. Should this be the case, it is likely to occur either at the logger or at the anemometer. A loose connection at the logger may be easy to repair, so the connection should be checked at the next visit to the mast.

Apart from the wind speeds, the wind direction data must also be checked for plausibility. The wind vanes are mounted at 37 m and 48 m above ground level. It is therefore expected that wind direction at both heights is roughly equal. Should the measurements diverge, a fault is likely to have occurred.

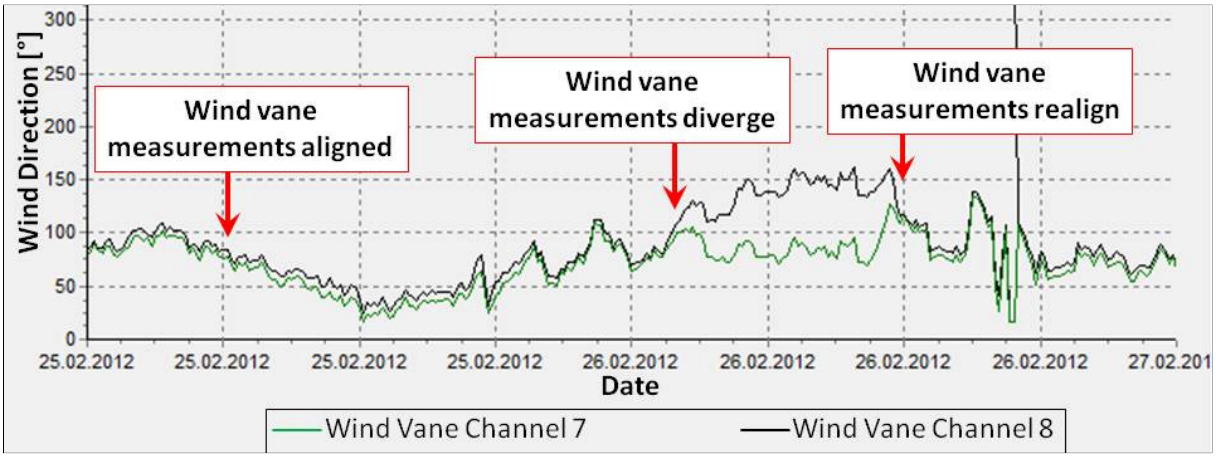


Figure 13 Wind direction measurements by the two wind vanes suddenly diverge by approximately 50°

As Figure 13 shows, wind vane measurements are mostly aligned, but a divergence of wind directions seems to occur between the 37 m and the 48 m levels for a period of approx. 10 hours, after which the measurements realign. Faulty equipment is most likely the cause of the divergence. This theory is supported by the fact that the first major misalignment occurs as late as January 2012 and therefore 17 months after the commissioning of the wind mast. After this point in time, the misalignment is recorded repeatedly and it frequently exceeds 30°. It is highly unlikely that winds at this height above ground show a diversion of this magnitude.

Due to the misalignment, data from both wind vanes was deleted where

- wind speeds exceed 3.5 m/s according to channel 14 (making them relevant for the wind turbine) and
- the misalignment is greater than 30°.

Apart from the deletions mentioned previously, no data is available for the period from 24 March to 15 April 2012. During this time, the data logger's battery was depleted. Some broken measurements had been recorded, but were deleted as the data was not reliable.

In summary, multiple errors were detected in the raw wind data. After the timestamps have been adjusted by adding 12 hours, data from wind speed and wind direction measurements were deleted where faults seemed to have occurred. No data was deleted from the channel 14 anemometer confirming its position as the primary wind speed sensor. The wind measurement campaign lasted for 22 months, but after cleaning the dataset only 94% of the measurement remains available for further processing. The channel 15 anemometer is an exception, as only 81% of the data could be recovered. Appendix 10 and Appendix 11 present a timeline of data availability.

The reviewed wind data is now validated and this cleaned dataset represents an accurate sample of the wind conditions found at the location of the wind mast. The characteristics of the dataset will be summarized in the following chapter.

4.1.3. Summary statistics

This chapter will summarize the wind regime that was recorded during the measurement period. Typically, this is done by compiling key figures and parameters which are sufficient for power output calculations and wind turbine generator selection.

A simple indicator often used to roughly describe the wind resource is the mean wind speed. This figure must however be treated with great caution, because the power output cubes with wind speed. Hypothetically, the following is true: If site A has a constant wind speed of 6 m/s every day for one year, it has a mean wind speed of 6 m/s. If site B has a constant wind speed of 12 m/s for half a year and 0 m/s for another half a year, it also has a mean wind speed of 6 m/s. Although the mean wind speeds for site A and B are equal, the theoretical power output of site B is 8 times higher than that of site A. Nevertheless, this value is used to compare wind resources on wind resource maps for example. Therefore, the mean wind speeds recorded during the measurement period are listed in Table 2.

Table 2 Mean wind speeds recorded by the wind data measurement campaign

Height above ground	Channel number	Mean wind speed	Mean wind speed	Channel number
50m	15	**6,5**	**6,6**	14
40m	13	**6,1**	**6,2**	3
30m	2	**5,4**	**5,3**	1

It is important to note that the mean wind speeds are always normalized to a one year period. This ensures that monthly variations do not distort the result. Merely averaging all recorded values would result in assigning too much weight to some months. Table 3 shows how the mean wind speed of the channel 14 anemometer is normalized to a one year period. The month of June is the only month covered only once during the measurement period. All other months were covered twice. Therefore, the mean wind speed for each month from January to December is calculated. Then the wind speed is averaged from the 12 mean values to render the normalized mean wind speed of a 1 year period.

Table 3 Calculation of the channel 14 anemometer mean wind speed which is normalized to a 1 year period

	Wind Speed [m/s] 2010	2011	2012	Mean wind speed per month [m/s]
January		6,2	6,4	6,3
February		6,1	5,9	6,0
March		5,4	6,1	5,7
April		5,5	6,7	6,1
May		6,4	7,9	7,2
June		6,6		6,6
July	7,7	5,9		6,8
August	6,6	7,1		6,9
September	7,3	5,7		6,5
October	7,4	6,4		6,9
November	7,6	7,7		7,6
December	7,4	5,6		6,5
Mean wind Speed for a 1 year period [m/s]				**6,6**

The mean wind speed varies significantly within a year. This characteristic may become important when matching the wind resource to the electric load curve, or to other sources of intermittent renewable energy e.g. the solar power resource. The monthly variation is depicted in Figure 14. Only mean wind speeds recorded on channels 1, 2, 3, 13 and 14 are graphed, because channel 15 measurements did not follow the general trend.

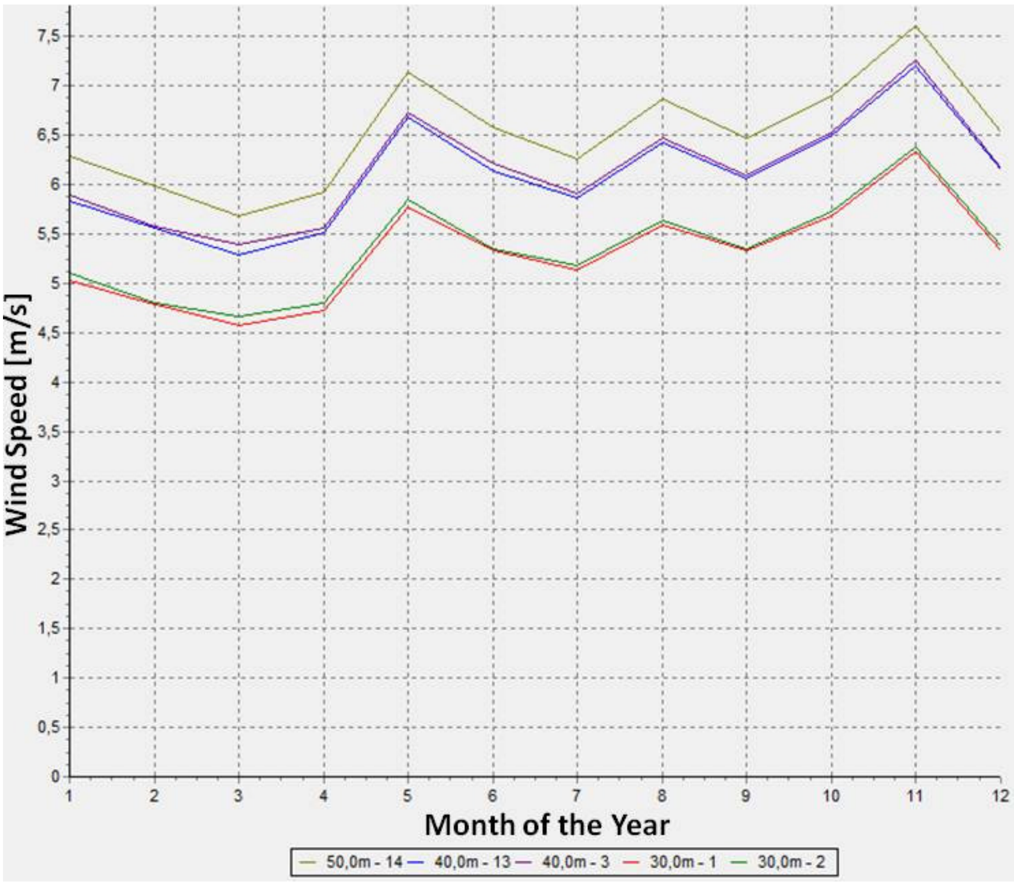


Figure 14 Monthly variation of mean wind speed measured by the Lapaha wind data monitoring campaign

The annual variation depicted above shows some differences in comparison to data analyzed in a previous study. The Lapaha wind data monitoring campaign measured the highest mean wind speeds in May and November while satellite data used by Vergnet in 2007 shows that May and November wind speeds were below average (see Figure 15). It is important to note that the points of the measurement or "Stations" for the Vergnet study were not located on Tongatapu but on open water. This example highlights the importance of conducting on-site measurements when planning a wind energy project.

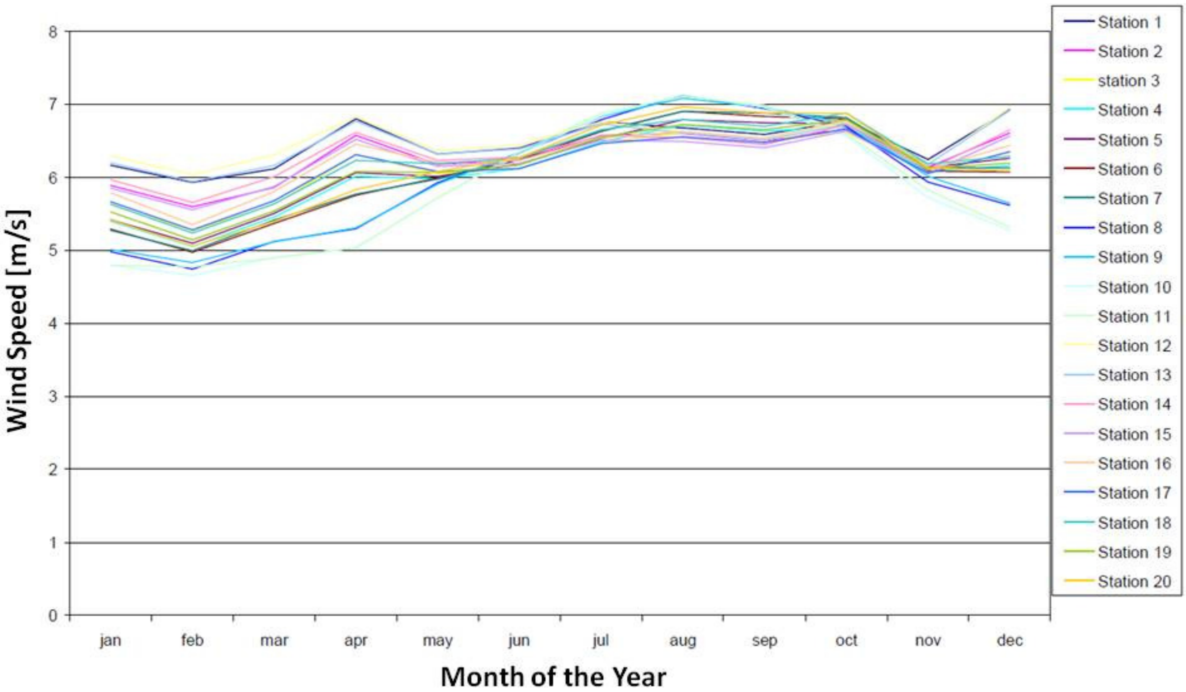


Figure 15 Monthly average wind speed from 1987 to 2001 (Vergnet Pacific, 2007)

As mentioned before, the mean wind speed can only convey limited information about the wind resource of a site. When calculations for power output are performed, either a wind speed histogram or a Weibull Probability Density Function (PDF) is used to describe the wind regime. Both, the histogram and the Weibull PDF are information sets which contain the probability of occurrence of a particular wind speed over a one year period.

Appendix 12 contains a list of binned wind speed records for the channel 14 anemometer. The wind speeds are categorized into bins with a bin width of 1 m/s. The table shows that only 2 out of the 91874 ten-minute wind speed records where between 24.5 m/s and 25.49 m/s (approximately 90 km/h). Encountering such high wind speeds at the location under study is therefore fairly unlikely. It is important to note, however, that higher wind speeds may have occurred during times where measurement data was invalid.

The advantage of describing the wind resource with a Weibull PDF is that the wind speed probabilities can be described using only two parameters. The Weibull PDF is defined in Equation 4.2. The shape parameter k defines the width of the curve while the scaling parameter A defines the height. Adjusting these two parameters allows compiling a Weibull PDF that closely matches the histogram found at a specific site. Typically this match is fairly close, but not exact.

$$p(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} \cdot exp\left[-\left(\frac{V}{A}\right)^{k}\right] \qquad 4.2$$

$p(V)$ = Probability of occurrence of wind speed V

k = Shape parameter

A = Scaling parameter (m s^{-1})

V = Wind speed (m s^{-1})

Figure 16 shows data collected from the channel 14 anemometer. An example of the information contained in the histogram is: A wind speed between 3.5 and 4.5 m/s has a probability of occurring in 12.6 % of the samples taken within a one year period. It is important to note that the best fit Weibull curve underestimates the probability of occurrence.

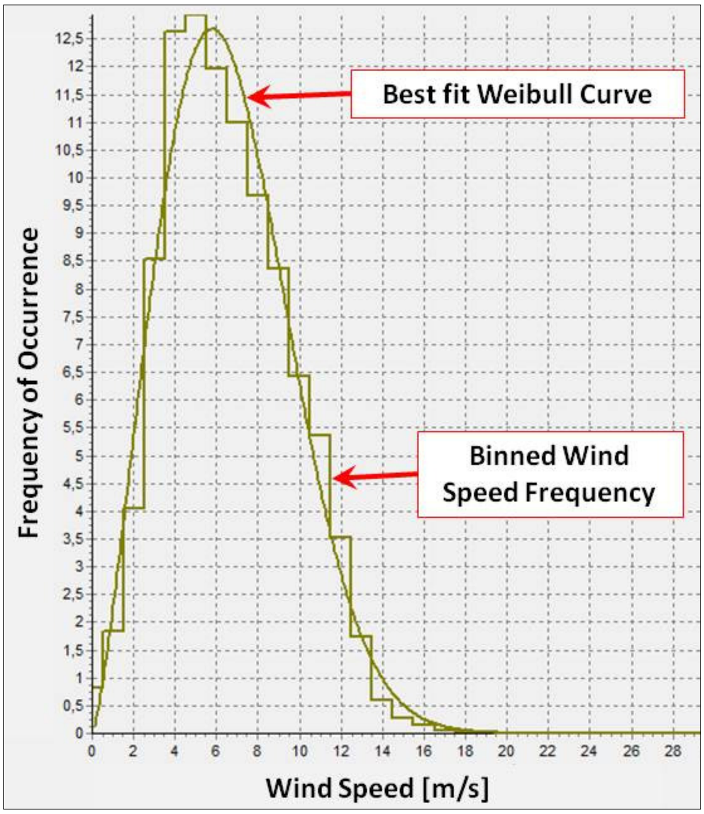


Figure 16 Histogram and Weibull curve of channel 14 anemometer

Although the Weibull PDF may not always be accurate, the parameters are often used to describe the wind resources of a site more accurately than merely stating the mean wind speed. The Weibull parameters identified for the Lapaha wind measurement campaign are listed along with maximum and mean wind speeds for each anemometer in Table 4.

Table 4 Key parameters describing the wind regime which was encountered during measurement campaign

Height agl [m]	Channel	Maximum wind speed [m/s]	Mean wind speed [m/s]	Weibull A parameter [m/s]	Weibull k parameter
30	**1**	21,3	5,3	6,07	2,1395
30	**2**	21,2	5,4	6,12	2,1527
40	**3**	23,8	6,2	6,99	2,1957
40	**13**	23,9	6,1	6,95	2,2056
50	**14**	24,8	6,6	7,44	2,2879
50	**15**	24,9	6,5	7,41	2,2368

The maximum wind speed encountered during the measurement period is fairly low at 25 m/s. Tonga does see tropical cyclones where wind speeds can be significantly higher. The danger of very high wind speeds should therefore not be underestimated.

Apart from extreme wind speeds, turbulence is also a concern for wind turbine selection. Turbulence can cause fatigue on mechanical parts and decrease lifetime while increasing maintenance requirements. Turbulence at the site under study is caused by the surrounding orography and roughness, but can also be caused by neighboring wind turbines. The turbulence intensity is defined as the ratio between the standard deviation of the wind speed, and the 10-minute mean wind speed as shown in Equation 4.3 (Thøgersen et al., 2011).

$$I_T = \frac{\sigma_u}{U_{10}} \tag{4.3}$$

I_T = Turbulence Intensity

σ_u = standard deviation of wind speed (m s^{-1})

U_{10} = 10-minute mean wind speed (m s^{-1})

The turbulence intensity measured by channel 14 anemometer is depicted in Figure 17. A more detailed study of turbulence and the wind turbine design requirements to withstand those turbulences will later be examined in the technical feasibility chapter of this report (see Chapter 5.2.2).

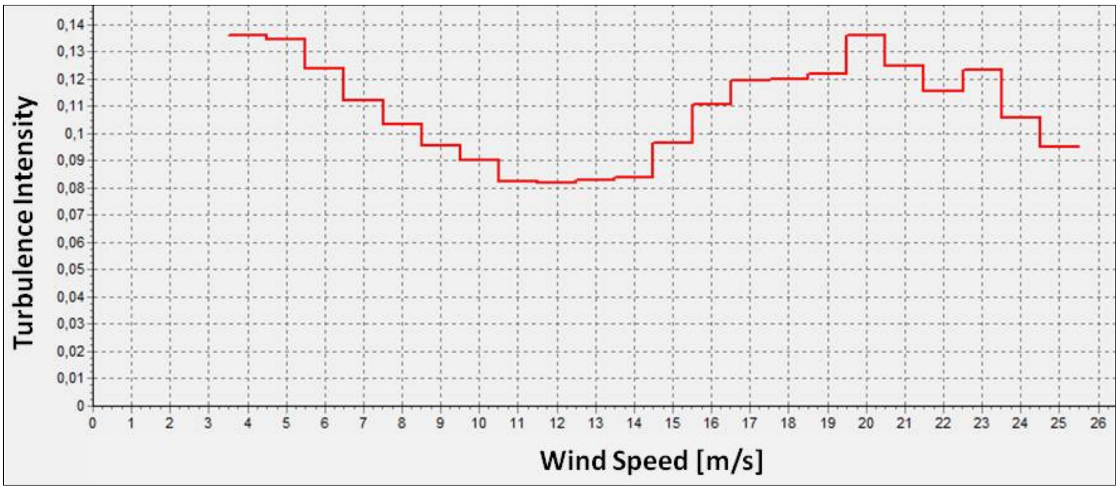


Figure 17 Mean turbulence intensity recorded by channel 14 anemometer during the measurement period

The wind direction measurements are important for wind park design (and compilation of a wind resource map). Of course a single wind turbine can utilize wind coming from any direction, but multiple turbines must be placed in a manner that takes the prevailing wind direction into account. This ensures that wake induced turbulences are minimized and energy production maximized. Typically, wind data is categorized into directional bins of 30° each. When the result is displayed graphically, the site's wind rose depicts the probability of occurrence of a certain wind direction.

Figure 18 shows the wind rose that has been sampled from the wind measurement campaign. The graph shows that the main wind direction is east with over 27 % of all wind records coming from that prevailing wind direction. This is in accordance with the results of the 2007 study, which found a similar wind direction distribution. Figure 19 shows the wind rose compiled by Vergnet. Both wind roses depicted here show prevailing winds coming from the east. The location of the wind monitoring mast is therefore well suited on the eastern side of Tongatapu, as the influence of the land surface is minimal in the prevailing wind direction.

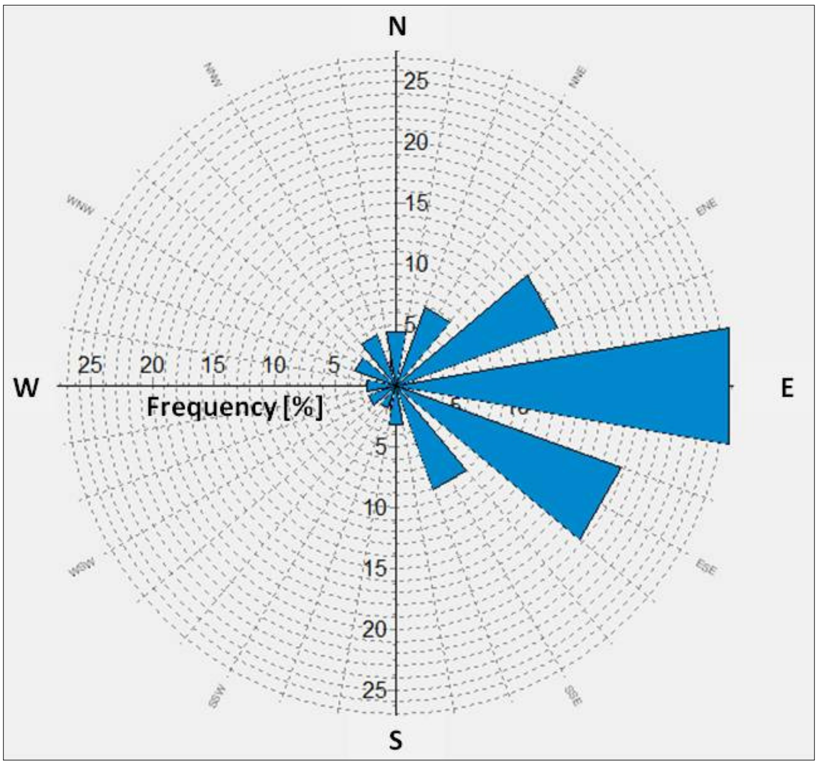


Figure 18 Wind rose recorded by the Lapaha wind measurement campaign

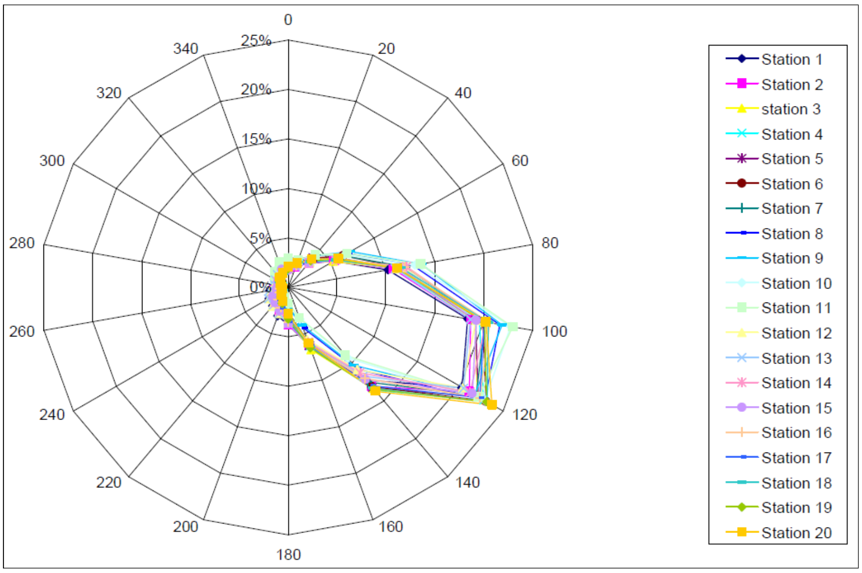


Figure 19 Wind rose of data from 1987 to 2001 (Vergnet Pacific, 2007)

In summary, the previous chapters describe the wind measurement data that was sampled during the wind data monitoring campaign at Lapaha. The most important figures and parameters were listed: A mean wind speed of 6.6 m/s was recorded for the channel 14 anemometer while the monthly mean wind speed varied significantly. The best fit Weibull curve has an A parameter of 7.44 m/s and k parameter of 2.2879. Maximum wind speeds did not exceed 25 m/s during the measurement, but tropical cyclones may very well incur much higher wind speeds. The prevailing wind direction was found to be east, which is in coherence with previous studies. It is important to note that the wind regime described above is merely a sample taken from a 22 months period. As annual mean wind speeds can vary significantly, the measured wind data has to be put into a long term perspective.

4.2. Long-term adjustment of the recorded wind speeds via Measure-Correlate-Predict

The wind measurement campaign recorded a dataset which reflects the wind regime that was dominating the location of the wind mast during the measurement period. Wind conditions can however differ significantly from year to year. Therefore, taking only the measurement period into account can lead to over- or underestimation of the wind resource. A common procedure of adjusting the measured wind data to reflect long term averages is the Measure-Correlate-Predict (MCP) method. Alternative methods are available, but will not be discussed within this study.

The MCP method establishes a mathematical relationship between a long-term reference dataset and the on-site data that was collected during the short-term measurement campaign. While the short-term data should be long enough to cover seasonal variation (i.e. 1 year) the long-term data should be “sufficiently long to eliminate short-term variations, probably at least 7 years” (IEC, 2005). Furthermore, the short-term and the long-term data must overlap entirely to allow assessment of the relationship.

4.2.1. Sources of long-term reference data

For the purpose of long-term wind regime predictions, three sets of data were obtained from two different sources (see Table 5). The data was accessed through EMD-online, a function within WindPRO that allows importing various sets of on-line reference data directly into the WindPRO project. While this method makes data access easy, it is important to note that the datasets can be downloaded freely from the sources listed without holding a WindPRO license.

Table 5 Overview of reference data

Data Type	Location of Data Point	Source
Measured	Fua'amotu Intl. Airport	Tonga Meteorological Service (TMS, 2012)
Reanalysis	135 km north of Tongatapu	National Center for Atmospheric Research (Kalnay et al., n.d.)
Reanalysis	145 km south of Tongatapu	National Center for Atmospheric Research (Kalnay et al., n.d.)

The first source of data is the Tonga Meteorological Service (TMS). TMS operates a meteorological station located at Fua'amotu International Airport, approximately 7.5 km south west of the Lapaha wind monitoring mast (see Figure 20). The TMS station measures wind speed and wind direction at 15 m agl.

Figure 20 Location of Tonga Meteorological Service's wind monitoring mast (Google Earth, 2012c)

During the site visit, the location of the mast was inspected and the geographic coordinates were recorded via GPS. Some obstacles like trees and the TMS office building were located in direct proximity of the mast. Furthermore, the wind vane and anemometer were mounted onto an ordinary light post. These conditions may distort wind speed and direction measurements. Figure 21 shows a photo of the vicinity of the mast as well as a close-up picture of how the anemometer and wind vane are mounted.

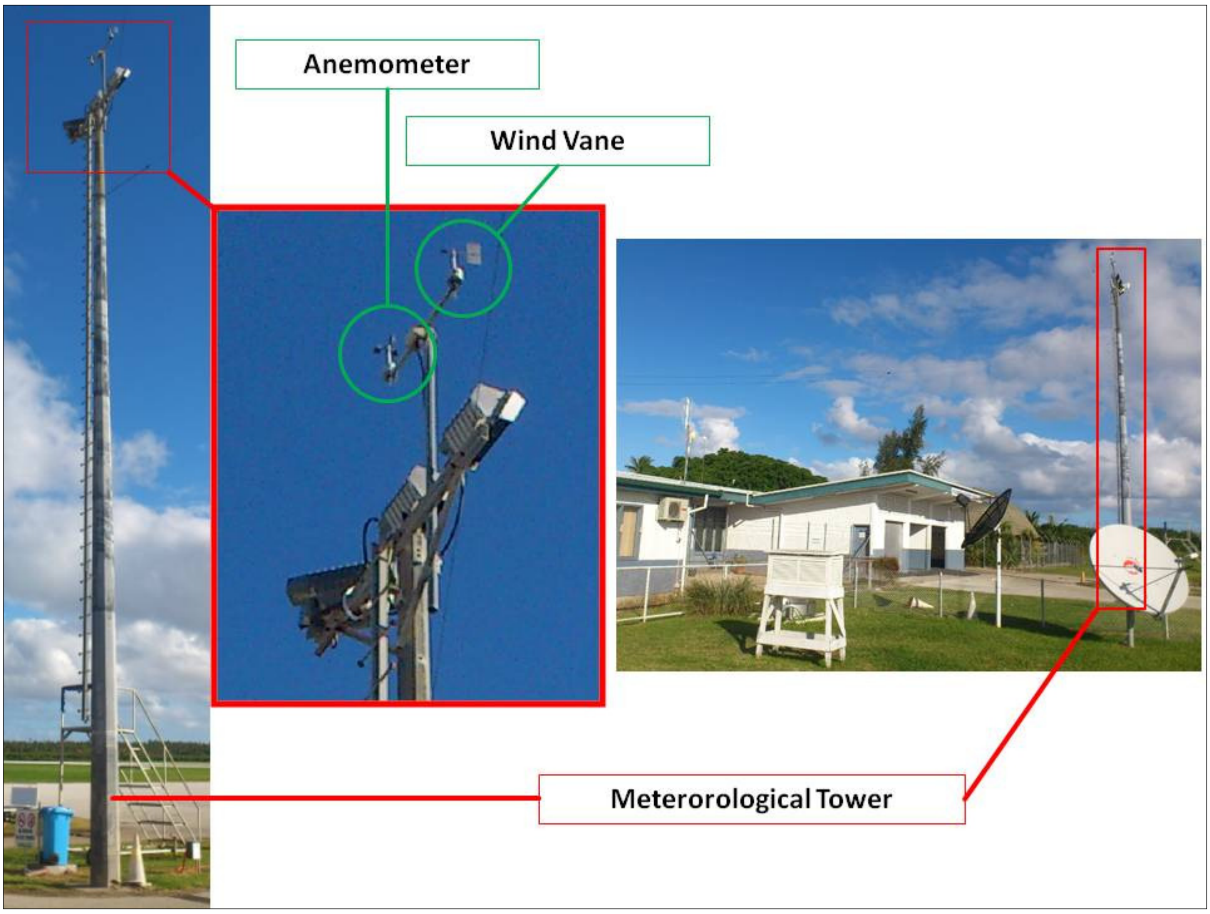


Figure 21 Photo of the wind monitoring mast operated by Tonga Meteorological Service at Fua'amotu International Airport (5 June 2012)

The Tonga Meteorological Service (TMS) was contacted and long-term data was requested. Unfortunately, the TMS staff stated that no long-term records were available in digital format. However, the TMS meteorological station continuously transmits its measurement via radio signal for input in weather reports. This signal is received and archived by the U.S. National Center for Atmospheric Research. Therefore, 3-hourly mean wind data from 1 October 1999 to 15 June 2012 were attainable by WindPRO's integrated data downloading option. The dataset for station number 91-792 was downloaded and sent to TMS staff who confirmed that the dataset had originated from the Fua'amotu meteorological station.

The second source of reference data is the NCEP/NCAR Reanalysis Project. This joint project between the United States National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) produces a historical as well as a current atmospheric analysis (National Weather Service, 2002). The database originates from a model that simulates atmospheric conditions at multiple grid points spanning the globe. In total, conditions at 192 x 94 points are simulated in 6 hour intervals.

It is important to note that the values produced are instantaneous rather than mean values. The manufacturer of WindPRO, however, claims that “there will be some ‘smoothening’ compared to real measurements” (Thøgersen, 2010b). The dataset is therefore deemed suitable for use in the MCP method.

Two sets of data from 1 January 1982 to 2 July 2012 were downloaded from the database described above using WindPRO’s integrated downloading function. One set of data was downloaded for the grid point 135 km north of Tongatapu, while the other set originated from a grid point 145 km south of Tongatapu (see Figure 22). Both datasets include wind speed and wind direction for height of 10 m above surface level.

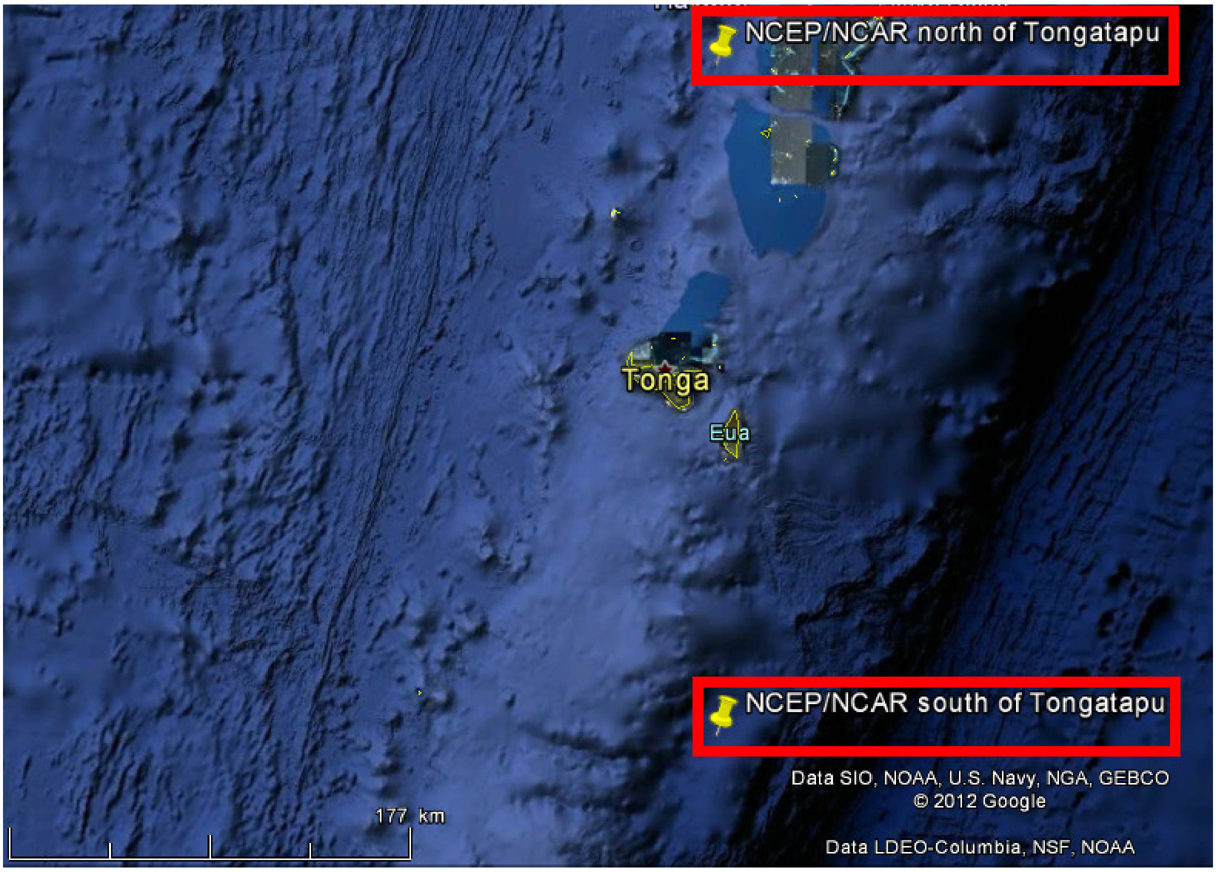


Figure 22 Map showing Tongatapu in relation to selected NCEP/NCAR data grid points

In summary, the Reanalysis Project and the Tonga Meteorological Service provide data that is significantly different from one another. Both datasets have some advantages and some disadvantages concerning their applicability as a long-term reference (see Table 6). As no preferred data source can be clearly identified at this point, all three datasets from both sources will be used for further analysis.

Table 6 List of advantages and disadvantages of using data from the NCAR/NCEP Reanalysis Project and the Tonga Meteorological Service as a long-term reference

	Advantages	**Disadvantages**
NCAR/NCEP Reanalysis Data	• Data covers a period of 30 years* • Model assimilates data from many different sources making errors from a single source less influential	• Values are instantaneous rather than mean values • Grid points are located over sea surface • Distance between grid points and Lapaha wind monitoring mast exceeds 130 km • Data interval is 6 hours
Tonga Meteorological Service Data	• Measurement is conducted close to Lapaha wind monitoring mast • Data covers a period of 12 years* • Data contains mean values • Data interval is 3 hours	• Surrounding environment may have interfered with measurements • Sensors are mounted on a light post and therefore not meeting international standards

*exceeding the recommended 7 year minimum period

It is important to note that the 3 datasets described in this chapter are not the only long-term references available in the region. More data points may be downloaded from the sources mentioned above and additional sources of potentially suitable long-term reference datasets were added to a new version of WindPRO during the course of this study. As a large portion of the work had already been completed when other long-term datasets were identified, time constraints prohibited taking these into account. It is recommended that any future wind resource assessment of Tongatapu analyzes the suitability of the additional long-term reference datasets.

4.2.2. Reference data validation

Before any dataset is used as a long term reference, the quality must be inspected to validate the dataset. Not only must obvious errors be deleted, but the source of the data should be questioned. EMD suggests performing the following evaluations of the data source (Thøgersen, 2010a):

- Is the reference mast sited in the same wind climate as the measure mast?
- Was the same equipment used during all years?

- Were the same measurement heights used during all years?
- Has the equipment been calibrated on a regular basis?
- Did the surrounding environment change during the years?

Tongatapu is relatively flat, so the TMS mast and the Lapaha mast are most likely located in the same wind climate. Concerning the equipment setup and calibration intervals reliable information could however not be obtained when TMS staff was interviewed.

Additionally, the change of the surrounding environment increases uncertainty. Tall trees with a thick canopy are located about 30 m east of the TMS mast and therefore in the path of the main wind direction (see Figure 23). Tree growth may have influenced wind speed measurements and introduced a bias. These possible sources of errors need to be considered in the further analysis.

Figure 23 Satellite image of the surrounding area of the Tonga Meteorological Service's wind monitoring mast

The first step to validate TMS data is to delete or modify apparent errors. Apparent errors are identified by plotting data in WindPRO. Suspicious data is then modified in Excel. The validated data is loaded into WindPRO and modifications are double-checked.

An apparent error in the data was found when the wind rose from the Lapaha and the TMS data were compared. While data from Lapaha showed only infrequent wind from the north, the TMS seamed to measure frequent winds coming from the north (see Figure 24). This error resulted from the wind direction being recorded as 0° (north) whenever the wind speed was at 0 m/s. Of course, a wind direction reading is superfluous when no wind is present. Therefore, all wind direction data was modified where the wind speed was equal to 0 m/s.

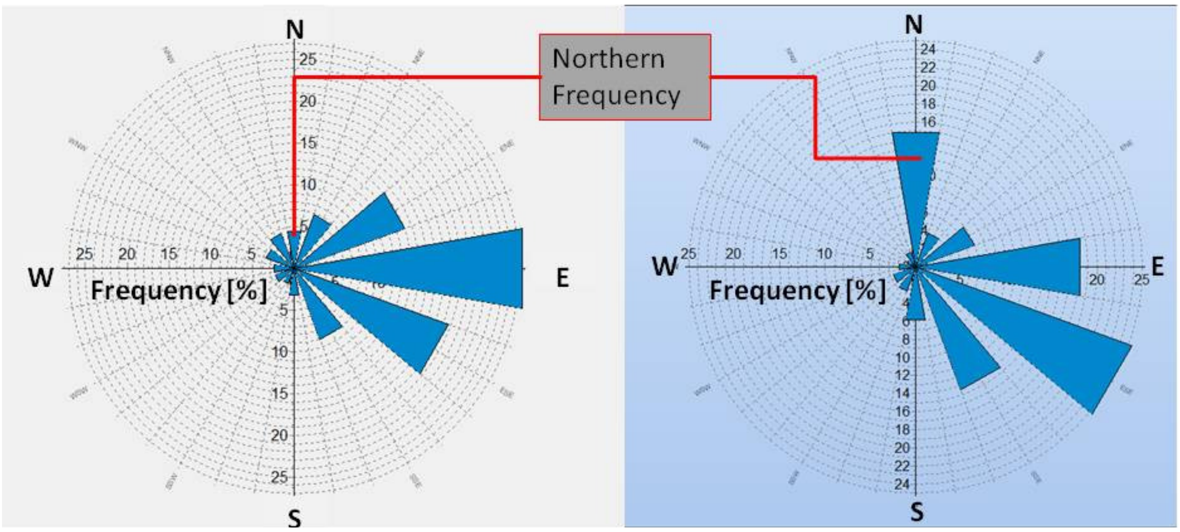


Figure 24 Comparison of wind direction frequencies of Lapaha wind monitoring mast (left) and Tonga Meteorological Service's monitoring mast (right)

Where wind speeds were recorded as 0 m/s a random wind direction was assigned. Merely deleting the wind direction would have caused WindPRO to regard the measurement as "out of range". This leads to an overestimation of wind speeds, because all 0 m/s wind speed records are rendered invalid. Assigning a random wind direction eliminates this effect. This correction will not have an adverse effect on wind energy calculations, as calms do not contain any energy.

The wind roses of Lapaha wind monitoring mast and the TMS airport monitoring mast are now fairly even, with eastern wind prevailing at Lapaha, and east south eastern wind prevailing at the airport (see Figure 25). The installer of the Lapaha mast, Clay Energy Ltd., was contacted and confirmed that the wind vanes had been correctly installed towards true north. The shift in prevailing wind direction between the data measured by TMS and the Lapaha wind monitoring mast was therefore not caused by an error in equipment setup but seems to reflect the wind regime correctly.

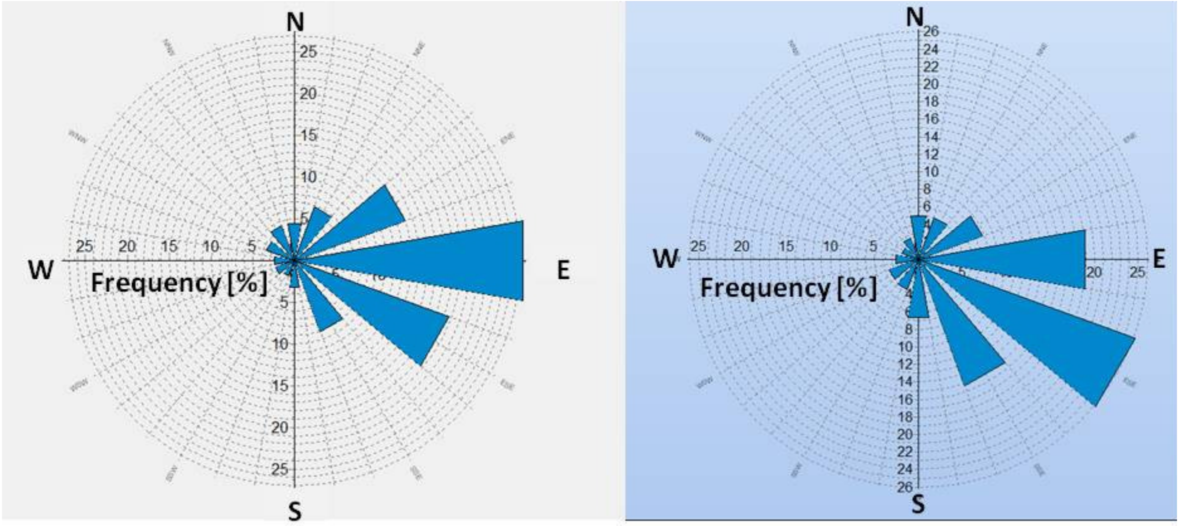


Figure 25 Comparison wind roses of Lapaha wind monitoring mast (left) and Tonga Meteorological Service's monitoring mast (right) after wind direction records of the latter have been corrected

Apart from the wind direction, the wind speed was checked for plausibility. Some extremely high wind speed recordings seemed to be the result of equipment errors. Sudden spikes in wind speeds up to 50 m/s seem unrealistic, considering that the records immediately before and after the extreme are not above average (see Figure 26). The entire time series was checked and all wind speeds above 40 m/s seemed erroneous and were therefore deleted.

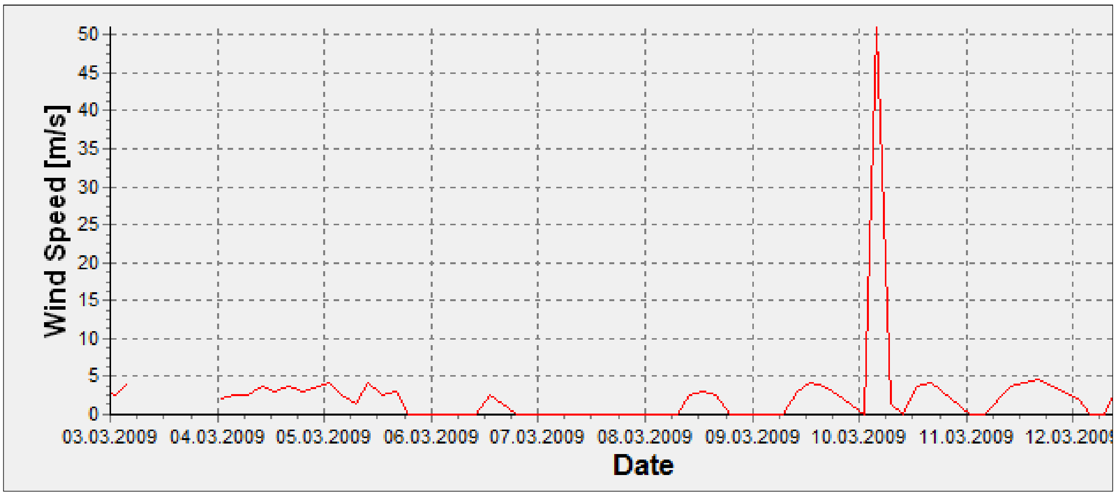


Figure 26 Error in data recording from Tonga Meteorological Service's wind monitoring mast

Another source of error was the transmission of the recorded wind data via radio. From February 2001 to July 2002 "Users found wind speeds that appeared to be approximately twice their actual value" (Schuster, 2003). During the respective period, wind speeds were recorded in knots, rather than m/s. Therefore, all wind speeds from 1 February 2001 to 30 June 2002 were converted to m/s (1.0 m/s = 1.94 knots). The resulting set of validated wind speed data is plotted in Figure 27. The depicted monthly mean wind speeds show that the green validated data is clearly more plausible than the red unvalidated data.

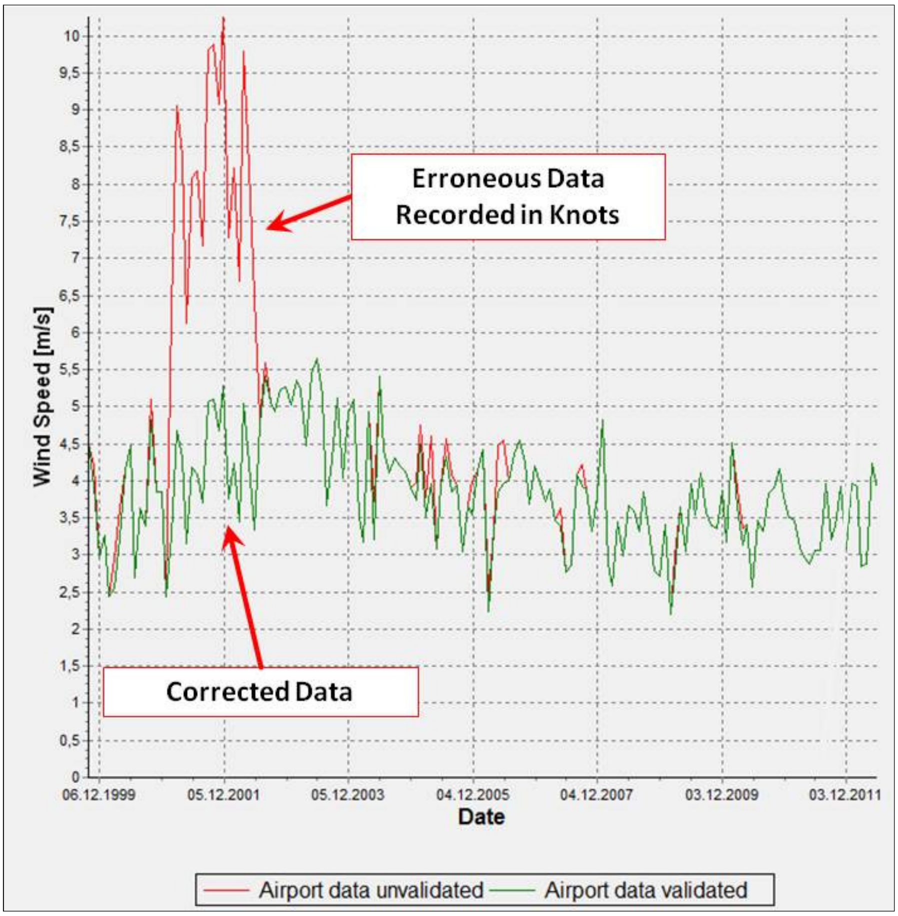


Figure 27 Comparison of validated and unvalidated monthly mean wind speeds recorded by TMS

While apparent errors in the TMS dataset were found and eliminated, no obvious errors were detected in either of the reanalysis datasets. Additionally, problem reports listed on the NCAR/NCEP Reanalysis Project website were briefly examined, but the data used in this study could not be identified as being erroneous (National Weather Service, 2002). Therefore, both sets of reanalysis data will be used as is.

In summary, only errors in data recorded by TMS were detected and the data was modified accordingly. The dataset is now validated and a total effective data period of 9 years is available for long-term wind speed predictions. Neither of the reanalysis datasets were modified and are therefore available for a period of over 30 years.

It is important to note that TMS data may still contain errors from lack of calibration or change of equipment, as no information on such activities was obtained. Additionally, the growth of trees within the main wind direction may have introduced a bias. The analysis described in chapter 4.2.3 will attempt to identify such errors in order to assess the suitability of the TMS dataset as a long-term reference.

4.2.3. Comparison of short-term and long-term reference datasets

Now that all datasets have been checked, a first comparison of data may put the Lapaha wind measurement campaign into a long-term perspective. The four datasets to be compared are summarized in Table 7.

Table 7 Overview of short-term and reference data used in the Measure-Correlate-Predict method

Data Use	Data Type	Data Period	Effective Period*	Location of Data Point	Source
Short-Term	*Measured*	*23 Jul 2010 to 31 May 2012*	*21 Months*	*Lapaha*	*Lapaha wind monitoring campaign*
Reference	Measured	1 Oct 1999 to 15 Jun 2012	109 Months	Fua'amotu Intl. Airport	Tonga Meteorological Service (TMS, 2012)
Reference	Reanalysis	1 Jan 1982 to 2 Jul 2012	366 Months	135 km north of Tongatapu	National Center for Atmospheric Research (Kalnay et al., n.d.)
Reference	Reanalysis	1 Jan 1982 to 2 Jul 2012	366 Months	145 km south of Tongatapu	National Center for Atmospheric Research (Kalnay et al., n.d.)

*excludes invalid data

Figure 28 shows the short-term wind speed data collected at Lapaha in comparison to the three long-term reference datasets. All plots depict 12 month rolling averages. The Lapaha wind measurement campaign was clearly conducted during a period of below average wind speeds. Both reanalysis datasets (north and south of Tongatapu) correlate very closely. Wind speed data collected from the airport also follows the general trend of wind speeds recorded by the reanalysis datasets. The peak in wind speeds recorded by the Airport in 2003 is confirmed by a congruent peak in the reanalysis data. The amplitude of the wind speed peak recorded by the airport's data is however significantly larger than the amplitude of the peak recorded by reanalysis data. Furthermore, the reanalysis' data varies by 5% from year-to-year while the airport measurements show an inter-annual variability of 13%. This characteristic may be the result of an inconsistency in the airports measurement equipment setup.

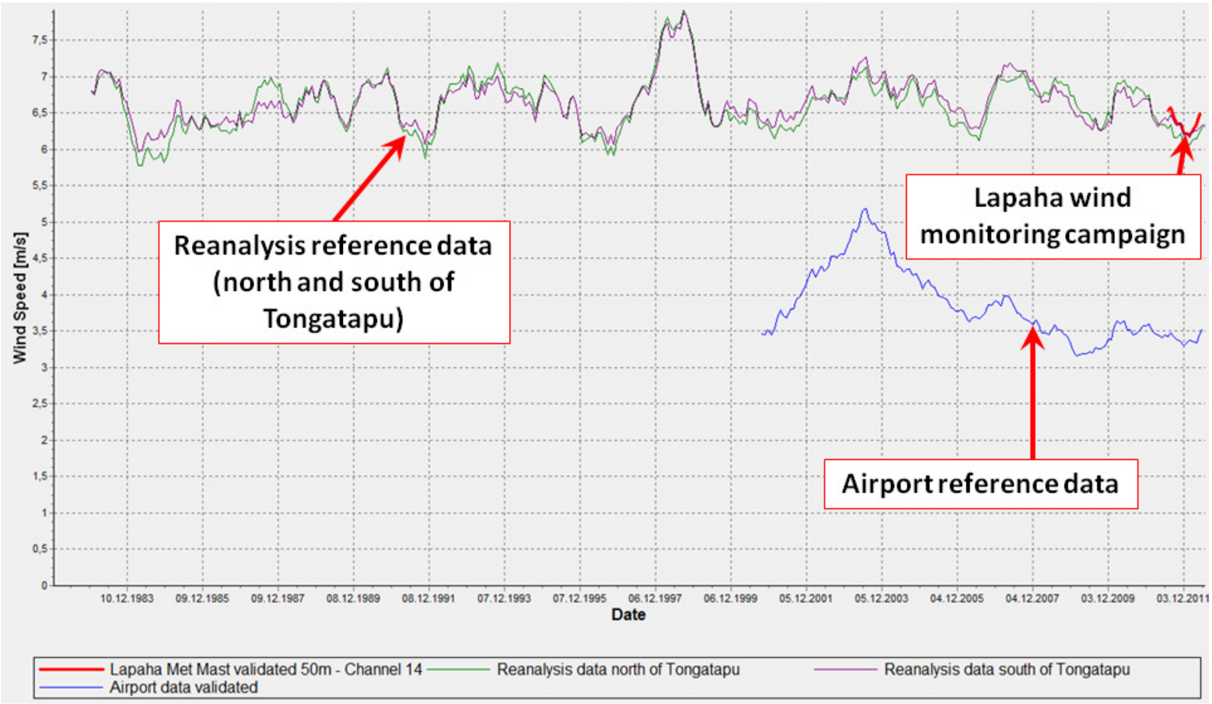


Figure 28 12 Month rolling average wind speed of Lapaha wind monitoring campaign and three sets of reference data putting the short-term measurement into a long-term perspective

In order to assess the consistency of the wind speed data measured at the airport, the correlation between the airport and the reanalysis data will be analyzed below. A gauge of correlation between two linearly dependent sets of wind speed data is the Correlation Coefficient r, where r is between 0 and 1.

When two wind speed datasets correlate perfectly, then the applicable linear transfer function can predict the wind speeds at one site precisely, if the wind speed at the other site is known. In this case the Correlation Coefficient r is equal to 1. When the prediction is less precise, a lesser correlation incurs a smaller r value closer to 0. The quality of a reference dataset may be determined by comparing the Correlation Coefficient to the classification listed in Table 8.

Table 8 Classification of r-values for the purpose of determining the quality of correlation (EMD, 2012c)

Correlation Coefficient	Quality of reference
0,5 to 0,6	Very poor
0,6 to 0,7	Poor
0,7 to 0,8	Moderate
0,8 to 0,9	Good
0,9 to 1,0	Very good

The wind speeds observed at Fua'amotu International Airport differ from those predicted by the reanalysis data points north and south of Tongatapu. Figure 29 compares the correlation of daily average wind speeds for the airport and reanalysis datasets from the year 2000 to 2011. Generally, the daily mean wind speeds measured at the airport have a higher correlation with the southern, rather than the northern reanalysis data point. Both correlations do however follow the same trend. While the southern data point correlation varies from 'poor' to 'good', the northern values vary from 'very poor' to 'moderate'. No definite trend can be identified in the depicted graphs. The spike in correlation in 2001 seems to be within normal variation, as a similar spike can be observed in 2010. A change in the airport's measurement equipment setup can therefore not be concluded.

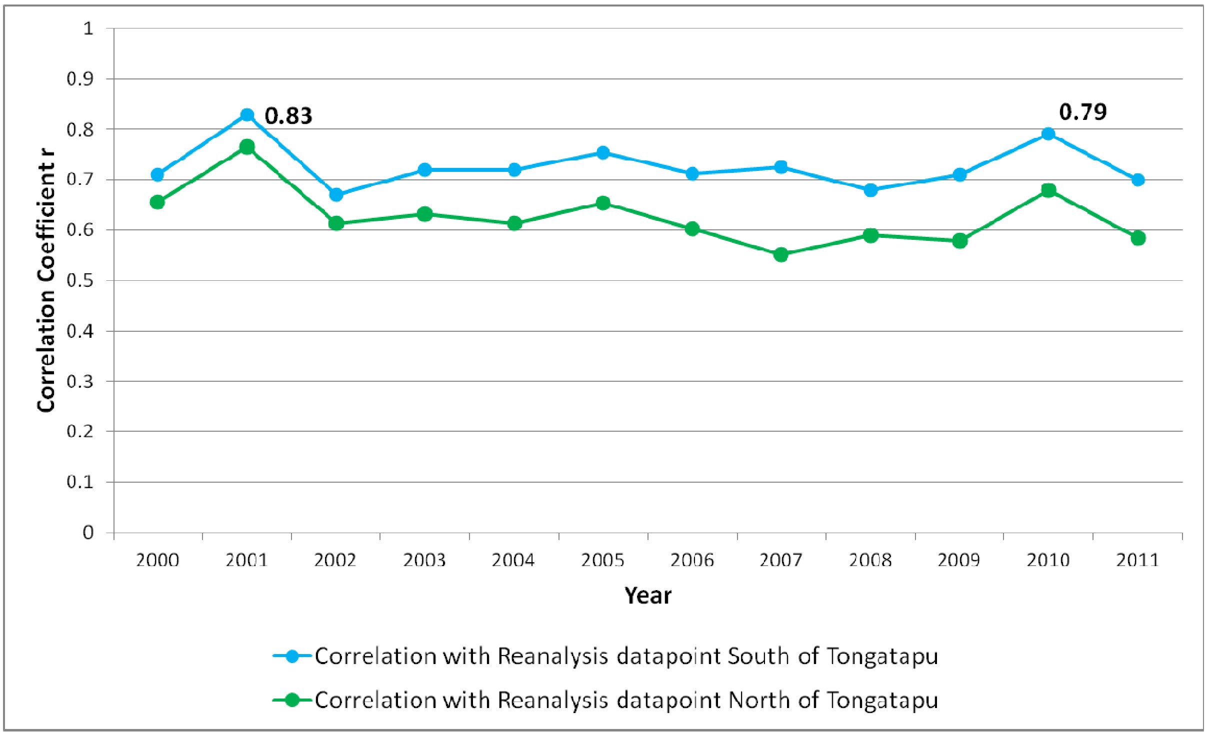


Figure 29 Correlation Coefficient of daily mean wind speeds obtained from Fua'amotu International Airport and NCEP/NCAR reanalysis datasets

As stated above and shown in Figure 28, the amplitude of the wind speed peak recorded in 2003 was larger in the airport's dataset in comparison to the values contained in the reanalysis data. However, a fault in the airport's dataset is unlikely, because correlation coefficients of 2003 do not differ significantly in comparison to those of other years.

It is important to note, that only the Correlation Coefficients of the daily mean wind speeds are plotted here. Nevertheless, Correlation Coefficients between TMS and NCEP/NCAR reanalysis datasets were analyzed for averaging intervals ranging from 6-hourly to monthly. The trends found in those correlations match the trends depicted in Figure 29. No sudden change in correlation was detected in the year 2003. The high wind speeds in that year are therefore considered plausible and the entire TMS dataset suitable as a long-term reference.

In the South Pacific region it is important to take El Niño and La Niña effects into account. These long-term phenomena have a significant influence on the climate and “average wind speeds drop considerably” (Factor 4 Energy Projects GmbH, 2010). The United States based National Oceanic and Atmospheric Administration (NOAA) states that the phenomena are characterized by sea surface temperature in a specific region (5°N - 5°S, 120° W – 170° W). The Oceanic Nino Index (ONI) is used to identify El Niño and La Niña episodes: If the 3 months rolling average sea surface temperature is equal or greater than +0.5°C in comparison to the long-term average, then this period is defined as an El Niño event. If the 3 months rolling average sea surface temperature is equal or less than -0.5°C, then this period is defined as a La Niña event (NOAA, 2012).

The below average wind speeds recorded during the Lapaha wind monitoring period may be linked to the occurrence of a La Niña event during that period. Historical ONI values listed in Table 9 show El Niño events in red font while La Niña events are depicted in blue font. The measurement period of the Lapaha wind monitoring campaign (outlined in red) was dominated by periods characterized as La Niña events.

Table 9 Oceanic Nino Index from recent years with the period of the Lapaha wind monitoring campaign outlined in red (NOAA, 2012)

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2002	-0.2	0.0	0.1	0.3	0.5	0.7	0.8	0.8	0.9	1.2	1.3	1.3
2003	1.1	0.8	0.4	0.0	-0.2	-0.1	0.2	0.4	0.4	0.4	0.4	0.4
2004	0.3	0.2	0.1	0.1	0.1	0.3	0.5	0.7	0.7	0.7	0.7	0.7
2005	0.6	0.4	0.3	0.3	0.3	0.3	0.2	0.1	0.0	-0.2	-0.5	-0.8
2006	-0.9	-0.7	-0.5	-0.3	0.0	0.1	0.2	0.3	0.5	0.8	1.0	1.0
2007	0.7	0.3	-0.1	-0.2	-0.3	-0.3	-0.3	-0.6	-0.9	-1.1	-1.2	-1.4
2008	-1.5	-1.5	-1.2	-0.9	-0.7	-0.5	-0.3	-0.2	-0.1	-0.2	-0.4	-0.7
2009	-0.9	-0.8	-0.6	-0.2	0.1	0.4	0.5	0.6	0.7	1.0	1.4	1.6
2010	1.6	1.4	1.1	0.7	0.2	-0.3	-0.8	-1.2	-1.4	-1.5	-1.5	-1.5
2011	-1.4	-1.3	-1.0	-0.7	-0.4	-0.2	-0.2	-0.3	-0.6	-0.8	-1.0	-1.0
2012	-0.9	-0.7	-0.5	-0.3								
2013												

In summary, the comparison of the short- and the long-term datasets showed that wind speeds recorded during the Lapaha wind monitoring campaign were below average. This assumption was confirmed by the concurrent occurrence of La Niña events during the respective period, where lower wind speeds are typically observed. The dataset measured at the airport generally follows the trend of wind speeds of the reanalysis sets.

The entire available period of data acquired from Fua'amotu International Airport will be used for long-term reference purposes. A relevant change in correlation between the TMS and the reanalysis datasets could not be detected, making it unlikely that changes in measurement equipment or change of environment have falsified the TMS data. The land based measurements in close proximity to the Lapaha mast are more reliable than a computer model output with grid points over the sea surface. Therefore, the estimation of the long-term wind resource performed in the following chapter will be taking the full extent of TMS data into account.

4.2.4. Measure-Correlate-Predict using the regression model

As was shown in the previous chapter, the wind measurements conducted at Lapaha recorded below average wind speeds. This characteristic proves the necessity to adjust the dataset to reflect long-term averages. This action prevents underestimation of the wind resource. The Measure-Correlate-Predict (MCP) methodology generally uses a fully overlapping set of long-term and short-term data to establish a numerical relationship between the two sets. The steps necessary to create such a relationship can vary, and many different methods can be found in literature. WindPRO features four methods that tackle the need for an MCP toolbox, while each method varies in complexity and computational requirements (Thøgersen et al., n.d.). Furthermore, the suitability of each method depends on the quality of reference data and the magnitude of the necessary adjustment.

The methods implemented into WindPRO are the Regression, the Weibull Scale, the Matrix and the Wind Index Method. In a comparison of two case studies, the WindPRO manufacturer EMD suggests using the regression or matrix method where ground data is available (e.g. the TMS data collected from the airport). Where long-term reference data is only available in sparse intervals (i.e. NCEP/NCAR reanalysis data) the Wind Index method is recommended. The Weibull Scale method is used best where only small adjustments are necessary and the frequency distribution fits the Weibull curve rather well (Thøgersen et al., n.d.). As the airport's ground based measurements are available, the Regression Method is selected to adjust the short-term wind speed records collected at Lapaha to the long-term level.

The linear regression method is performed using:

- long-term validated wind speed data collected at Fua'amotu International Airport
- short-term validated wind speed data collected by channel 14 anemometer at Lapaha

The regression model assumes that the wind speed at the measurement site (Lapaha) is dependent on the wind speed at the reference site (airport). This dependency is described by Equation 4.4 (Thøgersen et al., n.d.):

$$Y = f(x) + e \qquad 4.4$$

$Y =$ Wind speed at measurement site
$x =$ Wind speed at reference site
$f(x) =$ Regression model
$e =$ Random error (residual)

The equation used for $f(x)$ can be "polynomials of any order [...] but traditionally a linear model is assumed, as this model has been found to give reasonable fits for wind energy estimation" (Thøgersen et al., n.d.). The dependency between the wind speeds at Lapaha and the airport will therefore be described by the linear Equation 4.5:

$$Y = ax + b + e \qquad 4.5$$

$Y =$ Wind speed at measurement site [m/s]
$a =$ Slope of the line
$x =$ Wind speed at reference site [m/s]
$b =$ Y-Axis intersect of the line [m/s]
$e =$ random error (residual) [m/s]

The best fit linear equation is calculated for each 10° directional sector. This is necessary, because wind coming from different directions can be characterized by a different numerical dependency. As the wind direction data collected from the airport is rounded to tens of degrees, this interval is deemed appropriate. Therefore, WindPRO establishes a total of 36 numerical relationships between the wind speeds recorded at Lapaha and those recorded at the airport. The weighted mean of each sector's Correlation Coefficient is $r = 0.75$ classifying the quality of correlation between the Airport data and the Lapaha data as moderate.

Figure 30 plots congruent wind speeds coming from 90° (east) at Lapaha and the Airport. The straight green line is the best fit first order polynomial linear regression model. As not all points are situated on the line, the random error e (also known as residual) describes the vertical distance between each point and the line.

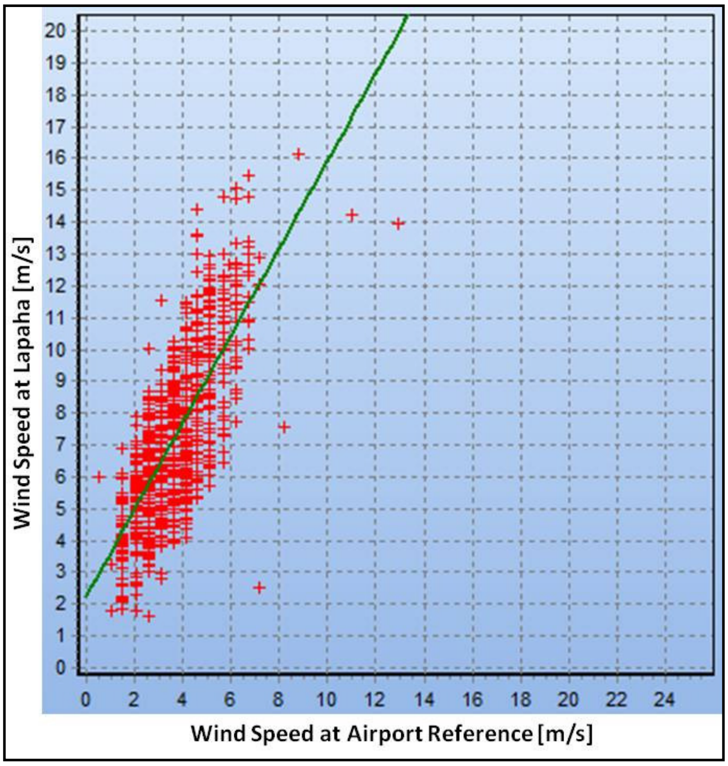


Figure 30 Linear relationship between wind speeds measured at Lapaha and those measured at the Fua'amotu International Airport. Only winds coming from 90° (east) are plotted.

In case residuals follow a zero mean Gaussian distribution, they need to be taken into account for predicting the long-term wind speeds. Otherwise "as much as 10% energy can be erroneously lost in long-term correction." (Thøgersen et al., n.d.). On the other hand, taking residuals into account while the errors do not follow a Gaussian distribution can lead to an overestimation of wind speeds.

Checking whether the residuals follow a zero mean Gaussian distribution is typically done by plotting residuals on a normal probability plot as in Figure 31 below, which shows residuals resulting from the linear regression depicted in Figure 30. If residuals were normally distributed, the plot would follow a fairly straight line. However, this is not the case. Therefore, the residuals do not follow a zero mean Gaussian distribution and may consequently not be taken into account when predicting long-term wind speeds.

Figure 31 shows only the 90° example of the 36 linear regressions performed, but residuals behaved similarly (non-linear) when graphed for other directions.

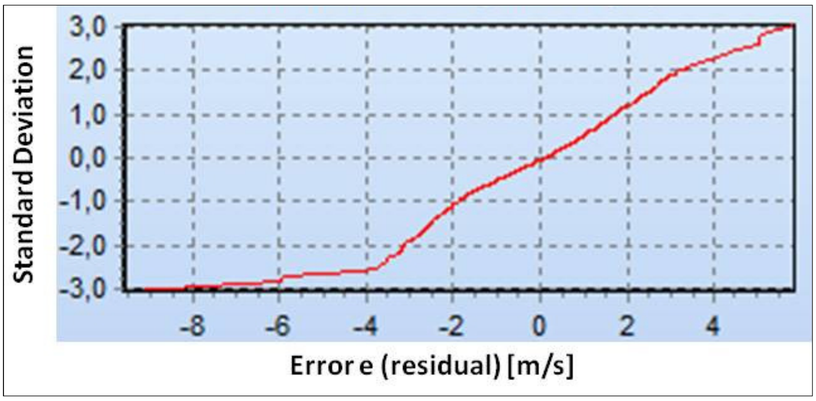


Figure 31 Normal probability plot of residuals resulting from linear regression of 90° (eastern) winds measured at Lapaha and Fua'amotu International Airport

The output of the Regression Method is an artificial long-term corrected time series that emulates a long-term measurement. This is created by applying the 36 linear transfer functions (dependency equations) to the long-term (airport) reference data. Depending on the selected model and parameters, the outcome can vary significantly. For the purpose of this study a number of different parameters were applied and models selected. All outcomes were checked for plausibility, but only the most refined long-term corrected time series will be discussed below.

4.2.5. Results of the regression method

As the transfer functions are applied to the long-term reference data, the product of the regression method has very similar characteristics in comparison to the original reference data. Two of the resulting long-term corrected datasets produced by the regression method are depicted in Figure 32. The shapes of the plotted 12 month rolling average wind speeds are closely related to the shape of the original airport reference data, with a high peak in 2003.

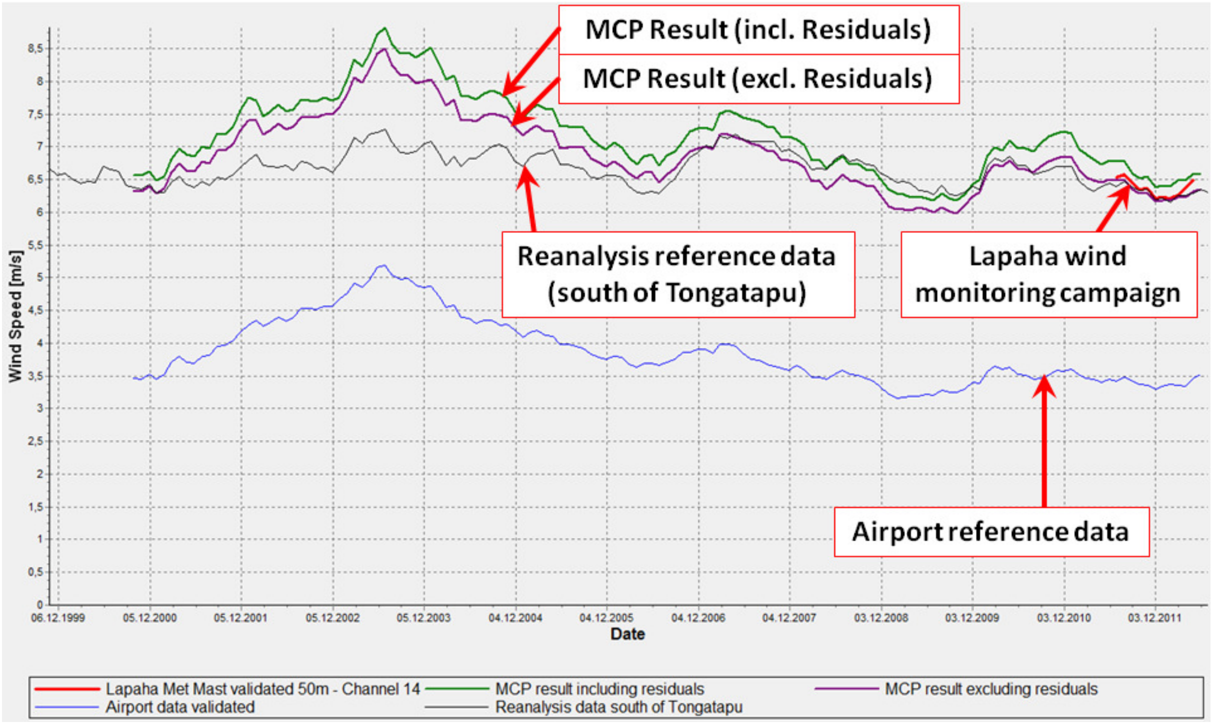


Figure 32 12 Month rolling average wind speeds of the regression method results in comparison to short- and long-term reference datasets

As mentioned in the previous chapter, predicted wind speeds tend to be higher if residuals are taken into account when establishing the numerical dependency. This characteristic is reflected in the comparison of the two long-term corrected time series. While all other parameters were kept constant, the wind speeds predicted by the MCP procedure including residuals is slightly higher than those wind speeds predicted when excluding residuals.

Notably, the lower MCP result curve (excl. residuals) correlates well with the actual measurements collected at Lapaha ($r = 0.83$). The correlation between Lapaha measurements and the upper MCP result curve (incl. residuals) is poor ($r = 0.66$). This distinction confirms that not taking residuals into account in this particular application of the regression method achieves accurate results and prevents an overestimation of the long-term wind resource.

The MCP result curve excluding residuals has been shown to be the most accurate prediction of long-term wind speeds. Therefore, this data will be used for further calculations. This artificial long-term wind regime is characterized by the parameters listed in Table 10.

Table 10 Key parameters describing the long-term wind regime predicted by applying the Measure-Correlate-Predict methodology

Mean wind speed [m/s]	Maximum wind speed [m/s]	Weibull A parameter [m/s]	Weibull k parameter	Duration [months]	Height agl [m]
6.8	29.8	7.64	2.3520	109	50

The mean wind speed of the long-term prediction is slightly higher (6.8 m/s) than the mean wind speed of the short-term measurement at Lapaha (6.6 m/s). This outcome was expected, as the Lapaha wind measurement campaign had been conducted during an episode of lower than average wind speeds (see chapter 4.2.3). It is important to note that the maximum wind speed of 29.8 m/s is the highest value that was generated within the artificial long-term corrected time series. In the event of a tropical storm, this wind speed may very well be exceeded.

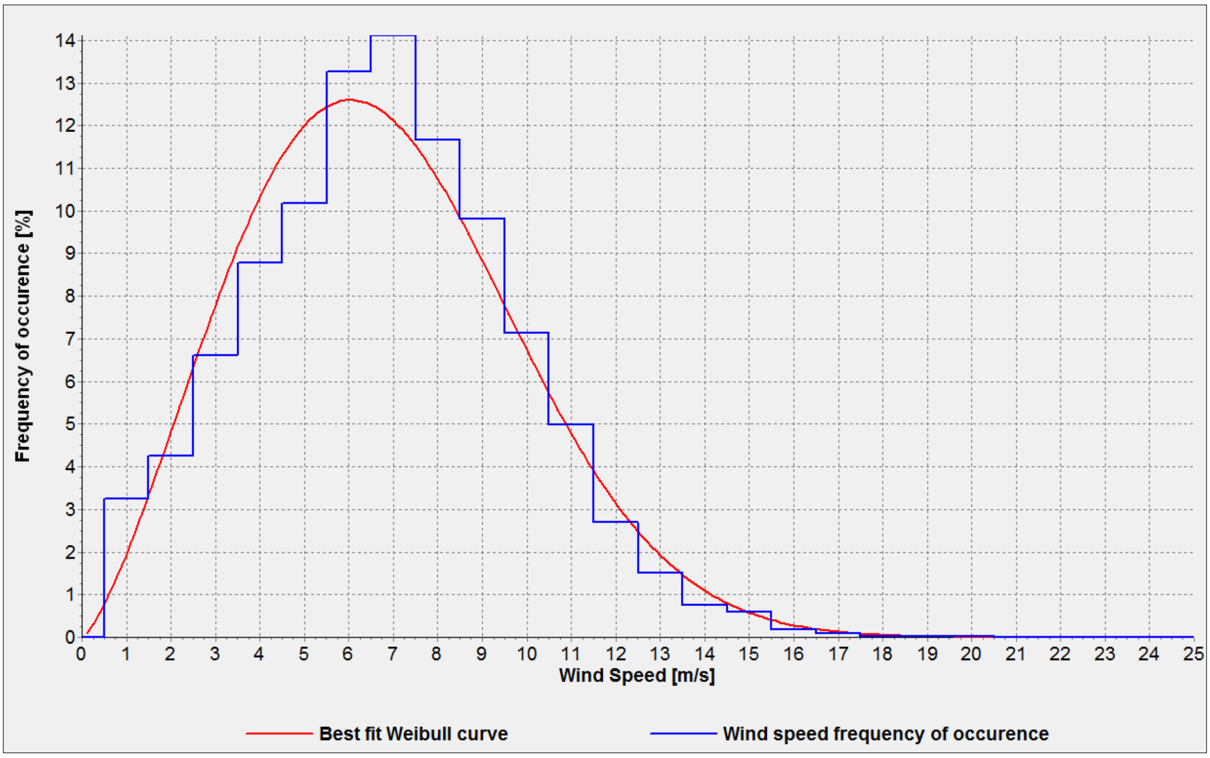


Figure 33 Histogram and Weibull curve of the long-term wind regime predicted by applying the Measure-Correlate-Predict methodology

As shown in Figure 33, the best fit Weibull curve does not match the histogram exactly. This wind regime characteristic seems plausible, as it was encountered when the histogram and Weibull curve of the Lapaha wind measurement campaign were compared (see chapter 4.1.3).

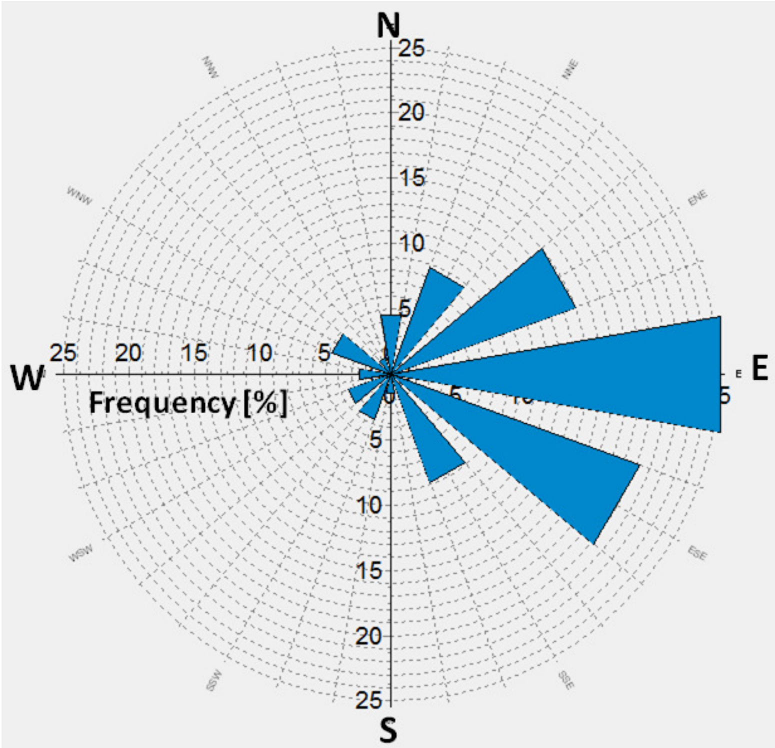


Figure 34 Wind rose of the long-term wind regime predicted by applying the Measure-Correlate-Predict methodology

The wind rose of the predicted long-term wind regime is shown in Figure 34. The prevailing wind direction is east, as over 25 % of all winds were recorded to have come from that direction. This characteristic is in line with expectations.

4.3. Summary of the wind resource assessment

The wind resource assessment concludes that the site under study has a long-term mean wind speed of 6.8 m/s at 50 m agl. This value is slightly higher than the mean wind speed of 6.6 m measured during the wind monitoring campaign. As suggested by previously conducted studies, the assessment found the prevailing wind direction to be east.

The wind data recorded by the Lapaha wind mast is of high quality and the mast meets necessary standards. Three sets of long-term reference data were compared for the purpose of long-term prediction of wind speeds. An analysis of yearly correlations between the three datasets found that reference data collected at Fua'amotu International Airport was reliable. Therefore, the linear regression was performed using the ground based reference dataset recorded at a nearby airport. The resulting long-term wind resource meets expectations in terms of wind speed and direction.

5. TECHNICAL AND ENVIRONMENTAL ASSESSMENT

The technical and environmental assessment proposes a wind farm design in Tongatapu to yield a maximum output of electrical energy, while considering environmental and technical constraints. The focus lies on the creation of a wind resource map which is compiled using the WAsP model. The map is used to identify those locations which yield the highest energy output. This task requires input of high quality terrain data to accurately extrapolate wind climate from the point of measurement to the points of interest.

Selecting the suitable type and number of wind turbine generators to be installed enables the design of a wind farm layout. The design process is constrained by a number of crucial criteria such as wind speed, wind direction and safety distance between turbines. Noise and shadow flicker impacts are assessed, in order to verify the suitability of the layout. Finally, the capacity factor, annual energy production and diesel fuel savings of the proposed wind farm are quantified.

5.1. Creating a wind resource map for Tongatapu with WAsP

A wind resource map typically shows long-term average wind speeds at different locations over a region of interest. The wind speeds are modeled for a specific height above ground, preferably a height close to the suitable wind turbine generator hub height. Such a map can be used to identify those locations which potentially yield the highest average wind speeds and therefore the highest energy outputs. A rough project area can therefore be selected on the basis of this map. Nevertheless, a detailed analysis of the energy output of each turbine will be necessary, as a wind resource map does not provide this information.

The wind resource map of Tongatapu was generated with the WindPRO software which uses the WAsP (Wind Atlas Analysis and Application Program) model. Introduced in 1987 by the Wind Energy and Atmospheric Physics Department at Risø National Laboratory in Denmark, the model has become an industry standard for wind resource assessment and wind turbine power production calculations. Although WAsP can be used as a standalone computer program, WindPRO adopts the model to allow its application within the WindPRO environment.

WAsP itself “contains several models to describe the wind flow over different terrains” allowing “vertical and horizontal extrapolation of wind climate statistics” (DTU, n.d.). Therefore, WAsP can predict the wind regime at any point within a given area where wind measurements are available at a single point only. It is important to note that the closer the predicted site is located to the point of measurement, the smaller the error will be in the prediction.

Figure 35 shows the approach WAsP uses to perform a horizontal extrapolation of wind climate from a point of measurement to a point of interest. First of all, the observed wind climate at the point of measurement is derived from the measured wind data. Secondly, the observed wind climate is cleaned from its surrounding environmental effects to obtain the generalized regional wind climate. This step requires digital models of the surrounding terrain. The resulting generalized regional wind climate is unaffected by the terrain and therefore assumed to be valid within a larger area. In order to predict the wind speeds at any nearby point of interest (i.e. the proposed location of a wind turbine), the process described above is reversed. Terrain effects are applied to the generalized wind climate to render the local, predicted wind regime at the point of interest.

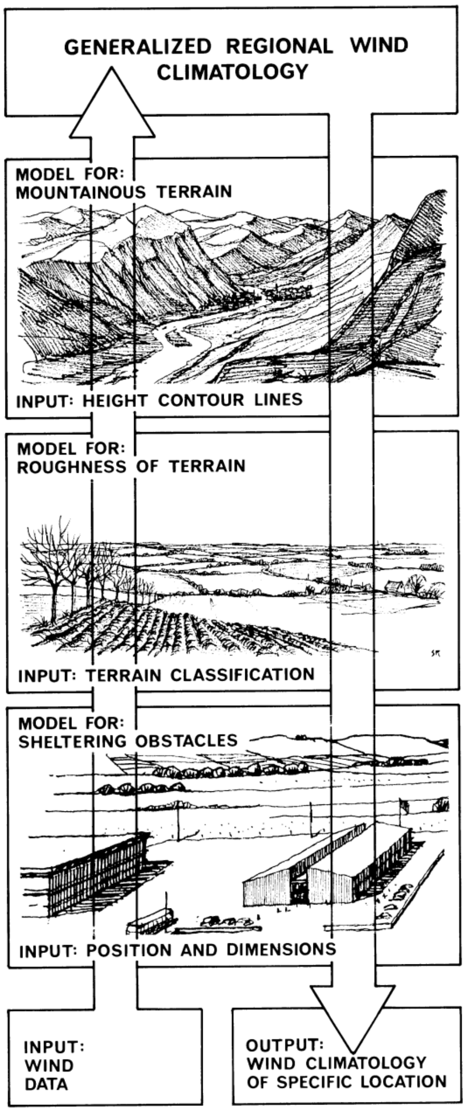


Figure 35 Description of steps applied by the WAsP model to predict wind speeds at any point of interest (Petersen et al., 1997)

Accurate models of the surrounding terrain are of great importance to an accurate extrapolation of wind climates to a point of interest. Typically, the terrain is described in three different sets of terrain models:

- Elevation
- Land cover
- Sheltering obstacles (optional)

While elevation and land cover are crucial input, modeling sheltering obstacles separately is not necessary. Land cover objects, like trees and buildings, decrease the wind speed depending on their height and porosity. Sheltering obstacles, like buildings or walls, have the same decelerating effect. Depending on the height of these buildings and their distance from the point of interest, obstacles may be included into the roughness model rather than establishing a separate model for sheltering obstacles (DTU, n.d.). Additionally, “WAsP's shelter model can handle up to 50 obstacles at the same time only” (DTU, n.d.). It is therefore not practical to utilize a model of sheltering obstacles for towns with many houses.

For these reasons, no separate model of sheltering obstacles was established for Tongatapu. All extrapolations of wind climates within this study are therefore based on the elevation and land cover models only. The purpose, application and modification of the elevation and the land cover models will be described in the following chapters.

5.1.1. Digital elevation model of Tongatapu

Taking the terrain elevation into consideration when assessing the cleaned, generalized regional wind climate is important, because wind speeds increase over smooth hilltops (see Figure 36). On the one hand, this implies that wind turbines placed on top of smooth hills yield a maximum amount of energy. On the other hand, a wind monitoring mast located on a hill top will measure higher wind speeds in relation to those in the surrounding area. Taking this bias into account avoids over- or underestimation of the wind resource.

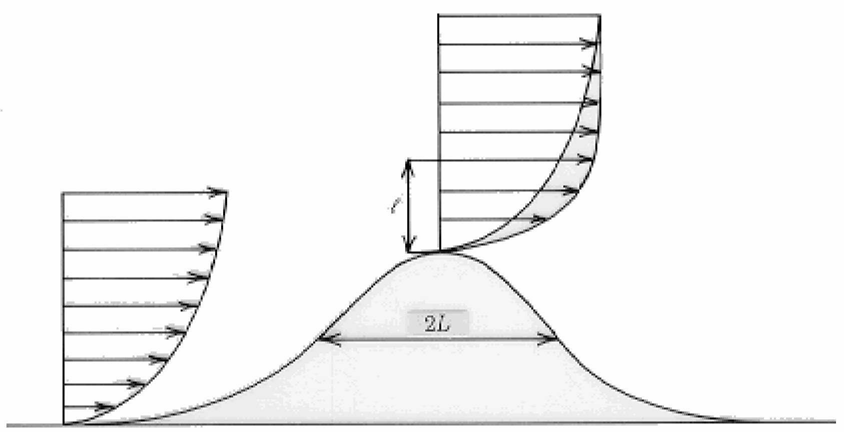


Figure 36 Wind speed increase over a smooth hilltop (DTU, n.d.)

Typically, terrain elevation is described by height contour lines. All points on a contour line are characterized by the same elevation. An electronic file containing these contours together with their geographical coordinates is known as a Digital Elevation Model (DEM). The DEM of Tongatapu was kindly provided by the Tongan Ministry of Lands, Survey, Natural Resources and Environment.

The DEM's meta-data states that "the layer was digitised from 1:25,000 scale topographic maps compiled in 1975". Although some changes may have occurred through erosion since the year of creation, no up-to-date data was available in similar quality. Figure 37 shows the elevation contours of Tongatapu and an enlargement of the area around the Lapaha wind monitoring mast. The interval between contours is 5 m, but WindPRO is able to extrapolate the elevation of any point between the contour lines via triangulation. The quality of these contours is deemed suitable for wind energy calculations.

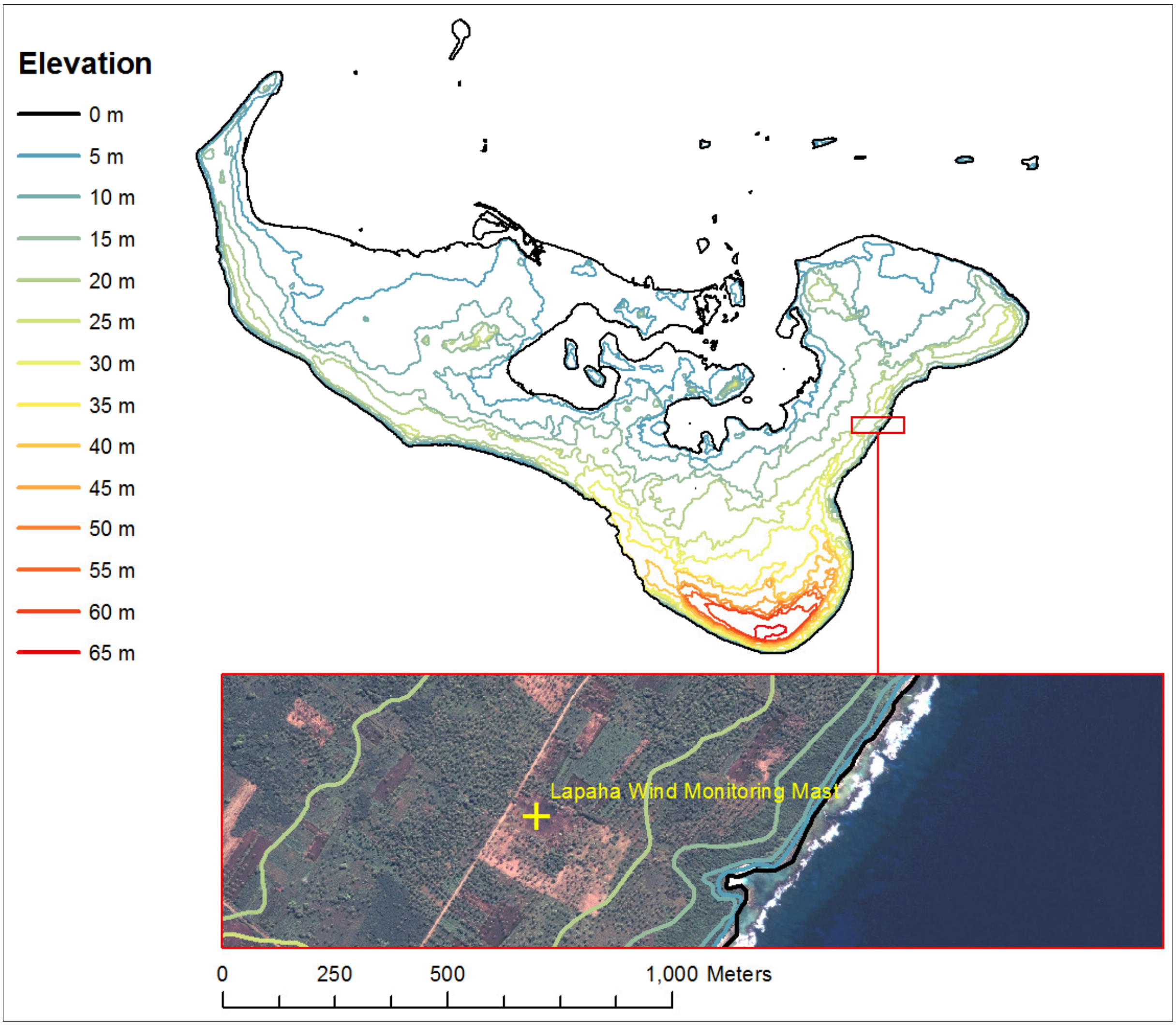


Figure 37 Digital Elevation Model of Tongatapu depicted as contour lines

It is worth mentioning that that the United States National Aeronautics and Space Administration (NASA) provides more recently compiled elevation data for almost any location on earth. NASA's Shuttle Radio Topography Mission (SRTM) data may be used when no alternative DEM is available. However, the SRTM data covering Tonga contains only one elevation point every 90 m, a quality generally not sufficient for wind energy extrapolations. The DEM used for the purpose of this study will therefore be the dataset provided by the Ministry of Lands, Survey, Natural Resources and Environment.

Before the Ministry's DEM could be used in the production of a wind resource map, some modifications were required. First of all, the 0 m elevation contour had to be merged with the remaining contours of 5 m to 65 m, as these had been provided in two separate files. Secondly, the 0 m elevation contour had to be modified in parts, because the original contour intersected other contours at some points. An intersection leads to errors in the WindPRO software. Figure 38 shows an example of how the original 0 m elevation contour (black) was modified (orange) in correspondence with the satellite image. Several corrections of this kind were required before all intersections had been resolved.

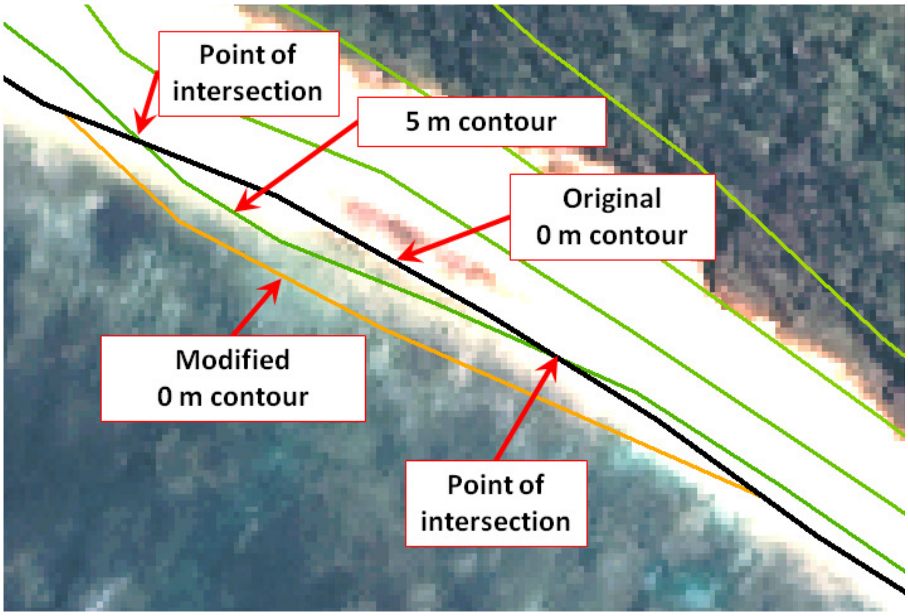


Figure 38 Example of the modification performed on the 0 m elevation contour

It is important to note that the complexity or smoothness of terrain limits the applicability of the WAsP model. WAsP always assumes airflow over hills to be attached (laminar). However, terrain with very steep slopes or sudden drops may cause airflow to detach and become turbulent. WAsP is not able to model these conditions, leading to inaccurate wind climate predictions. However, the DEM depicted in Figure 37 above shows that Tongatapu is relatively flat. Nevertheless, the shore on the eastern side of the island was investigated during a site visit, because the transition between water and land on this side of the island affects those winds coming from the main wind direction.

Appendix 13 depicts two photographs from two different locations on the eastern shore of Tongatapu. The images show that erosion has formed a steep drop of approximately 3 m to 5 m. Due to prevailing easterly wind, this type of small cliff is a typical feature encountered on the eastern side of the island. However, a 5 m drop is not considered to interfere with the laminar wind profile at relevant heights of 50 m.

Apart from terrain complexity, the WAsP model is also limited by the assumption that the regional wind climate is valid everywhere within the area under study. This may not be true in mountainous terrain, as climate can vary from one side of a mountain to another. Since, however, Tongatapu's highest point is approximately 65 m above sea level, the wind climate over Tongatapu is not separated by topography. Therefore, neither complexity nor mountainous areas limit the applicability of the WAsP model on Tongatapu.

5.1.2. Digital land cover model of Tongatapu

Wind speed is not only affected by the elevation of terrain, but also the height and porosity of land cover. While a few dispersed bushes on an otherwise open plain will inhibit the free flow of air by only a little, a thick forest slows down the wind significantly. WAsP uses a digital land cover model to take the effect of land cover into account. Such a model encircles areas covered by similar types of vegetation or construction to group these into classes with similar characteristics.

The digital land cover model of Tongatapu that is used for the purpose of this study was kindly provided by the Tongan Ministry of Lands, Survey, Natural Resources and Environment. Figure 39 shows the land cover model of Tongatapu and an enlargement of the area around the Lapaha wind monitoring mast. The land cover data is of high resolution and separated into 16 different classes.

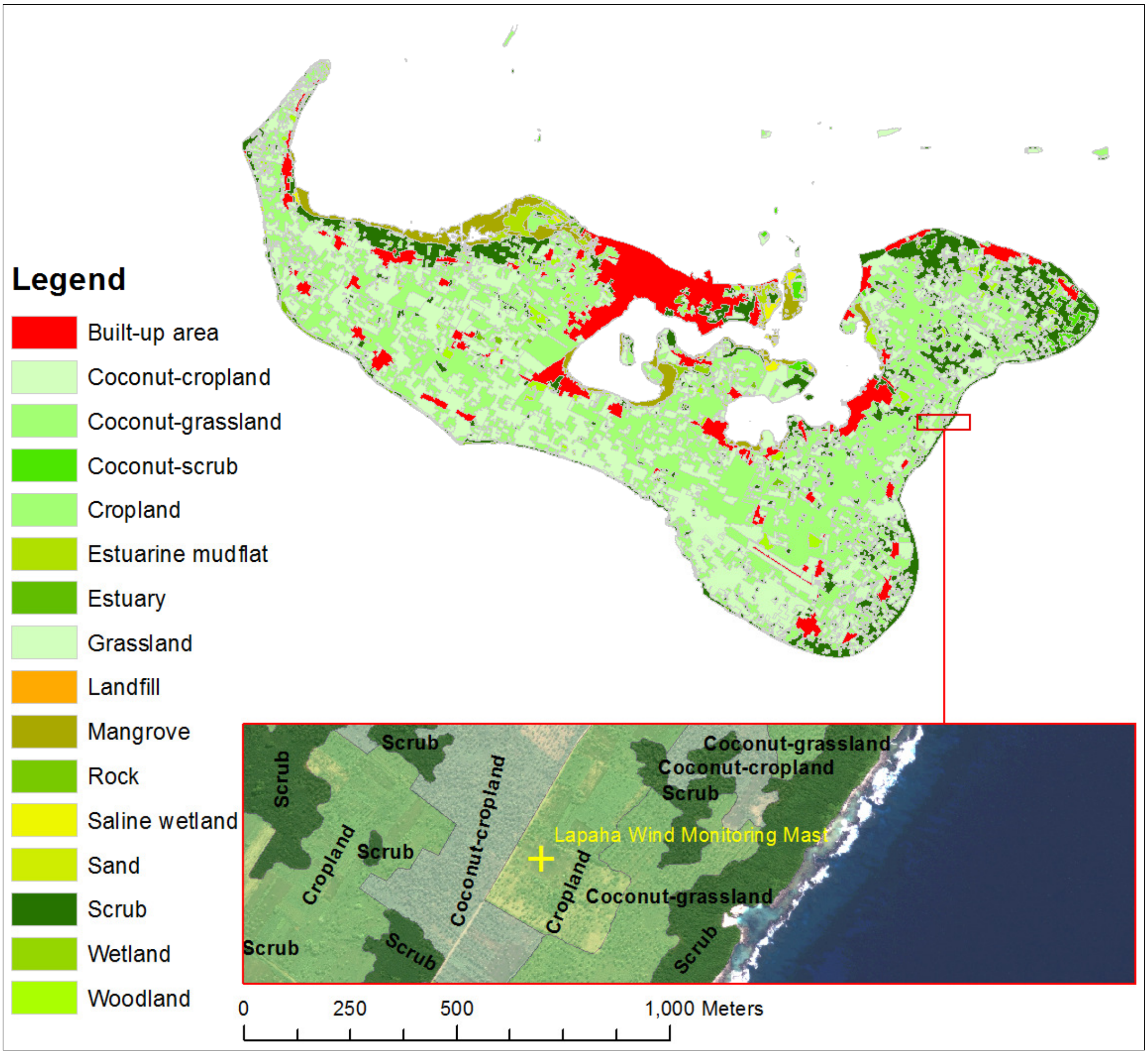


Figure 39 Land cover model of Tongatapu

The ministry's meta-data states that land cover "was mapped from […] QuickBird satellite imagery dating from January 2003 to March 2006." Therefore, some parts of the digital land cover model are based on data collected almost 10 years ago. Nevertheless, time constraints prohibited an update of land cover data to be performed within the limited scope of this study. Consequently, the resulting wind resource map may not reflect accurate wind speeds in areas where land cover has significantly changed in recent years.

A comparison of some land cover areas with Google Earth imagery dated 2009 found significant deviations to occur only in the center of the island. As the coastal region is of much higher relevance to wind energy applications, the land cover model used in this study is deemed suitable for the compilation of a wind resource map.

In order to comprehend how WAsP uses land cover data, it is important to understand that generally, the wind speed within the boundary layer of the atmosphere increases with height above ground. Moving air is decelerated close to the earth because land cover such as bushes, trees and buildings obstruct the free flow. Simplified, the vertical increase in wind speed can be assumed to follow a logarithmic profile as depicted in Figure 40.

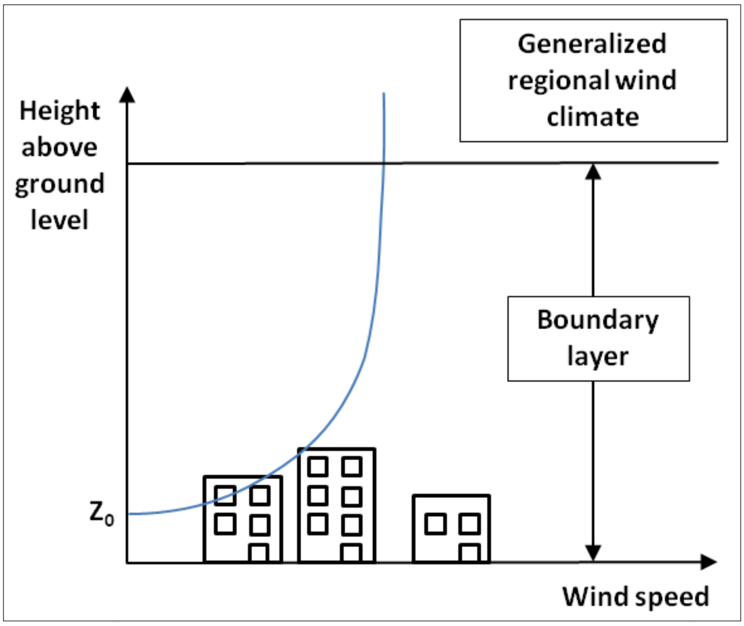


Figure 40 Sketch of logarithmic wind speed profile

The sketch above shows that the air can flow freely above the boundary layer, because it is unaffected by land cover. WAsP can calculate the generalized regional wind climate by cleaning the measured wind speed from the decelerating effect of the surrounding land cover.

Mathematically, this decelerating effect is quantified by the roughness length z_0. The higher the roughness length, the lower the wind speed at a specific height. It is important to note that the roughness length is a conceptional value that can only be estimated, but not determined exactly. “Formally, z_0 is the height where the mean wind speed becomes zero, if the wind profile has a logarithmic variation with height.” (DTU, n.d.). Therefore, variations in the roughness length are reflected as variations in the shape of the vertical wind speed profile.

When the land cover’s roughness length z_0, the measured wind speed v_1 and the measurement height h_1 are known, then the wind speed v_2 at any other height h_2 can be determined by Equation 5.6 (Richert, 2010):

$$v_2 = v_1 \frac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}} \qquad 5.6$$

v_2 = Wind speed at height h_2 (m s^{-1})
v_1 = Wind speed at height h_1 (m s^{-1})
z_0 = Roughness length (m)

It is important to note that the land cover model does not contain roughness length information. As this information is required by the WAsP model, appropriate values need to be assigned manually.

The European Wind Atlas describes a mathematical method to estimate roughness lengths involving the height and wind-facing cross section of roughness elements (Troen et al., 1989). Nevertheless, this method is not deemed practical for this study, because height and cross section information of trees, bushes and buildings is not available. Therefore, roughness values for all land cover types are assigned according to a best estimate. These estimates are based on the following references:

- Satellite images
- Photographs and subjective impression collected during site visit
- Table of common land cover types and corresponding roughness lengths provided in the WAsP help (DTU, n.d.) (see Appendix 14)
- Sketches of common land cover types provided in the WAsP help (DTU, n.d.). An exemplary sketch is depicted in Figure 41.
- Roughness length values used in a previous wind resource mapping study conducted by Vergnet (Vergnet Pacific, 2007)

Figure 41 Reference sketch of farmland with many windbreaks separated by a few hundred meters. The corresponding roughness length is 0.4 m (DTU, n.d.).

Notably, the table and sketches of land cover types in the WAsP help have been derived from the European Wind Atlas (Troen et al., 1989) and do not match the tropical land cover types found in the South Pacific. A class like ‘Coconut-cropland’ is not listed in these references for example. Land covers of Tongatapu are therefore matched to those found in the references via best estimate.

A roughness length was assigned to each of the 16 classes found in the land cover model by employing the following procedure:

1. Viewing of land cover type under study on satellite image
2. Viewing of land cover type under study on photograph (where available)
3. Matching of land cover type under study to land cover type on table in WAsP help
4. Matching of land cover type under study to sketch in WAsP help
5. Matching of land cover type under study to land cover type used in Vergnet’s wind resource mapping study
6. Subjective weighting of roughness lengths determined by steps 3 to 5 and comparison with roughness lengths already assigned to previously processed land cover types.
7. Assigning of roughness length to land cover type under study

The result of the procedure described above is listed in Table 11. Here, a roughness length value has been assigned to each land cover class. In general, the values are significantly higher than those used in Vergnet's wind resource mapping study listed as 'Vergnet's value'. Therefore, the wind resource map compiled within this study will most likely show lower wind speeds than those predicted by Vergnet's in Figure 3.

Table 11 Roughness length values assigned to the land cover model

Land cover class	Roughness length [m]	Vergnet's value [m]	Comment
Built-up area	**0.5**		like suburbs with many windbreaks
Coconut-cropland	**0.4**	0.3	very dense, but not as dense as forest
Coconut-grassland	**0.3**	0.3	palm trees are sparser than on Coconut-cropland
Coconut-scrub	**0.8**	0.3	like a forest, very dense because of scrubs in between the coconut palms
Cropland	**0.1**	0.2	like sketch: "farm land with wind-breaks"
Estuarine mudflat	**0.1**	0.1	few trees/bushes, mostly sand
Estuary	**0.03**	0.2	mostly shallow water with few mangroves
Grassland	**0.25**		a little more open than coconut-grassland
Landfill	**0.1**		very small area making it almost irrelevant
Mangrove	**0.3**	0.3	value taken from Vergnet
Rock	**0.1**	0.15	mostly quarry (mining) with some trees
Saline wetland	**0.2**		a few more bushes than Estuarine mudflat
Sand	**0.003**	0.1	taken from WAsP help
Scrub	**0.5**		very dense, but trees are not as tall as coconut trees
Wetland	**0.2**	0.2	like swamp, value taken from Vergnet
Woodland	**0.8**		similar to forest
Water	**0.0**		in WAsP water is defined to have a roughness of 0

It is important to note that Eua Island was not included in the land cover or the elevation model, because the data was not available. Although the island is significant in size, Eua's closest point is 18 km east south east of Tongatapu. For predicting wind climates at 50 m agl, land cover models with a 20 km radius and elevation models with a 5 km radius around the project area render sufficient results (EMD, 2012a). Consequently, Eua's effects on wind climates in Tongatapu are deemed very small and therefore negligible.

5.1.3. Compiling the Wind Resource Map

Now that roughness length values have been assigned to the land cover model and the digital elevation model is cleared of all faults, the wind resource map can be compiled.

The first step is to clean the long-term corrected observed wind climate of the terrain influences, to generate a generalized regional wind climate, also known as a wind atlas. A flowchart of the procedure employed by WAsP can be found in Appendix 15. Correctional factors for land cover (roughness) and elevation influences are calculated based on the terrain models described above.

Notably, WAsP does not only apply correctional factors for roughness and elevation, but also for atmospheric stability. However, the atmosphere over Tongatapu is assumed to be neutrally stable, an assumption deemed realistic over oceans and small islands. Therefore, all WAsP calculations in this study are performed using the default parameters as listed in the WAsP help (DTU, n.d.). No further investigation of the atmospheric stability was performed within this study.

After calculating the generalized regional wind climate, the second step in compiling a wind resource map is to predict wind climates at relevant points of interest. In order to obtain a local wind climate, WAsP applies the correctional factors to the generalized regional wind climate. A flowchart of this procedure can be found in Appendix 16.

A wind resource map is generated by arranging a number of points of interests into a grid. For the purpose of this study a grid point spacing of 25 m was selected to render a high resolution raster. The grid was clipped to those areas with an elevation higher than 0 m. In effect, the clipping ensures that the resulting shape of the wind resource map resembles the shape of Tongatapu. Additionally, clipping reduces computer processing time significantly, because vast areas of open water do not have to be processed.

When the local wind climates at each point of interest on the grid are calculated, the resulting dataset contains the long-term average wind speed at 50 m agl at every point on Tongatapu. Applying an appropriate color scheme to the dataset results in the wind resource map depicted in Figure 42.

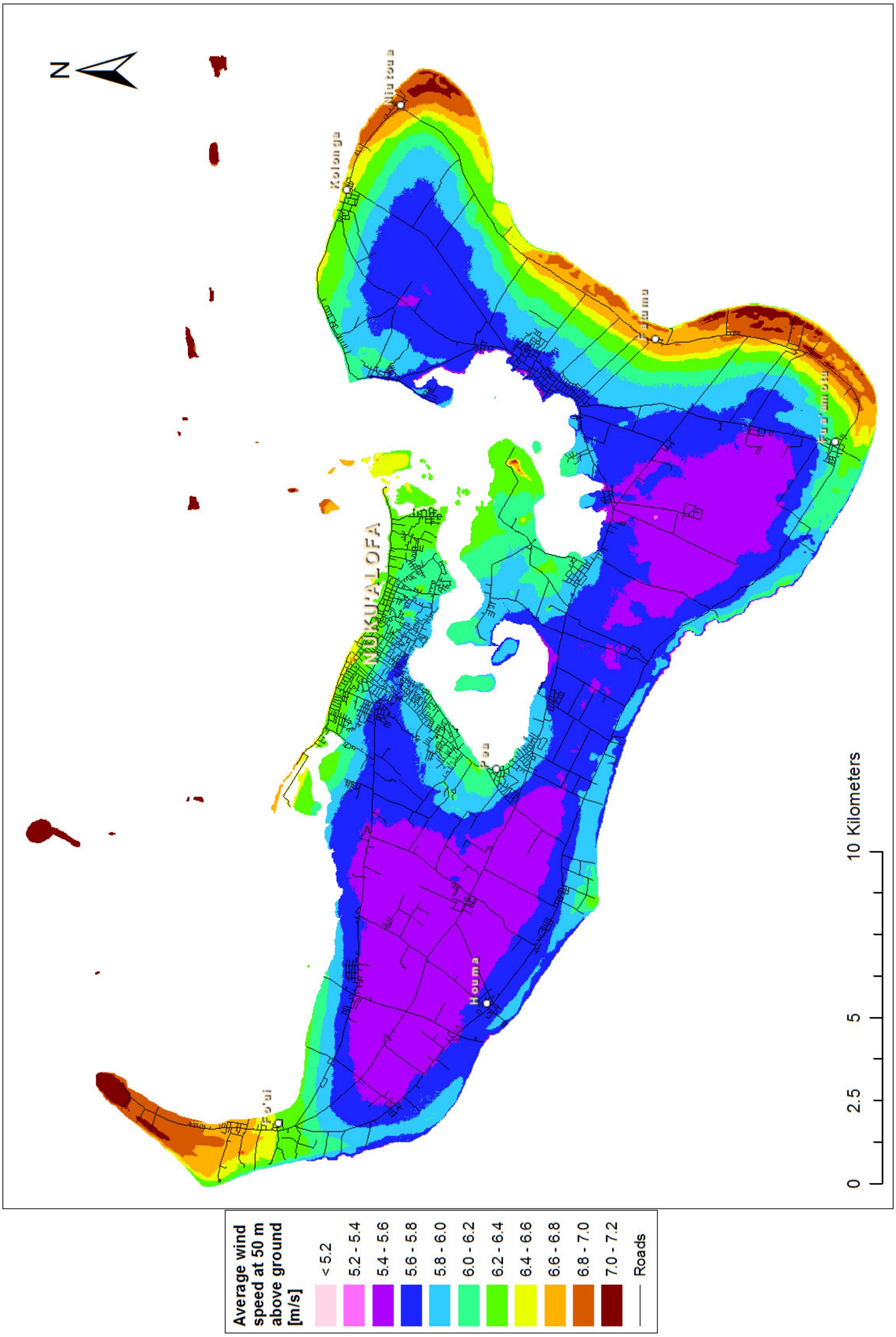


Figure 42 Wind resource map of Tongatapu

In line with expectations, the wind resource map of Tongatapu depicted above shows that wind speeds are highest on the eastern coastline. Average wind speeds decrease rapidly towards the center of the island, a characteristic caused by the dense land cover. At 50 m agl, the highest average wind speeds of 7 m/s to 7.2 m/s are found on the northeastern cape and the southeastern bend of the island. The northwestern peninsula also features average wind speeds above 7 m/s.

In comparison to the wind resource map compiled by Vergnet (see Figure 3), the areas with higher and the areas with lower wind speeds match those areas identified within this study. Nevertheless, the Vergnet wind resource map generally depicts higher wind speeds. This may be attributed to the fact that Vergnet assigned lower roughness length values (see Table 11). It is important to note, however, that the wind resource map compiled within this study is based on high quality measured wind data, realistic roughness values and high resolution terrain models.

Nevertheless, the accuracy of the wind resource map is still limited. Uncertainties stem from the WAsP model itself, partly outdated roughness and elevation data as well as uncertainty in the long-term corrected measured wind regime. While the map is most reliable on the eastern side of Tongatapu, the northwestern peninsula is 27 km from the Lapaha wind monitoring mast. The predictions of this wind resource map must therefore be treated with care and can only serve to identify those areas where further investigation of the wind resource seems feasible.

5.2. Design of a wind farm on Tongatapu

5.2.1. Selection of the total nominal wind turbine generator capacity

The total nominal wind turbine generator capacity is that amount of power produced by the wind farm if all wind turbine generators operate at maximum output simultaneously. This parameter should be as large as possible to maximize diesel fuel savings. However, the maximum power of the wind farm is constrained by the minimum grid load, the available spinning reserve and the maximum generator capacity of the PV power plant.

A 2010 study examined the maximum nominal wind turbine generator capacity that can be integrated into the Tongatapu electric grid under technical considerations (GHD Australia, 2010a). The simulation took into account that a diesel generator must be operating at all times to compensate for sudden fluctuations in renewable energy output. The study states that electric energy storage is not an economically viable option for Tongatapu, because its implementation would increase the cost of electricity considerably. Consequently, GHD concluded that the maximum installed wind power may not exceed the following:

- 1.4 MW nominal wind power if no PV generator capacity is installed
- 1.0 MW nominal wind power with a 2.1 MW PV generator installed

The assessment was based on Tongatapu's hourly electric load data from September 2008 to August 2009. The blue graph in Figure 43 shows the load curve that was used in this study. Apart from a few outliers, the load ranges from approximately 3500 kW to 8500 kW. Therefore, the combined output of the wind and photovoltaic generator do not exceed demand.

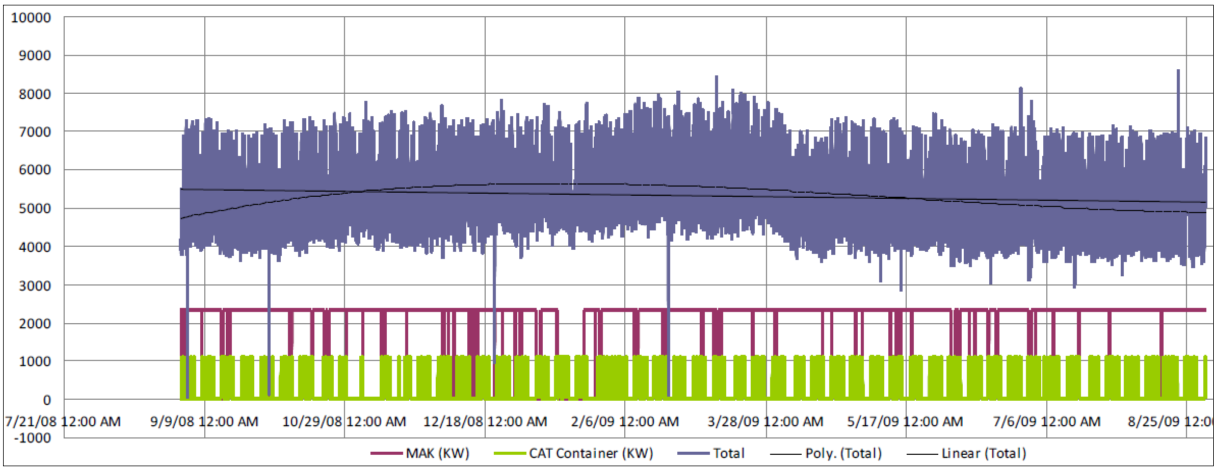


Figure 43 Hourly electric load curve of Tongatapu from September 2008 to August 2009 (GHD Australia, 2010a)

Although the load data has been collected over three years ago, the GHD's assessment still applies today. Recent half-hourly electric load data kindly supplied by the local utility Tonga Power Limited shows that the load curve has not changed significantly. The data graphed in Figure 44 nearly covers a one year period from 04 April 2011 to 29 February 2012. Apart from a few outliers, the minimum load lies at around 3500 kW while the maximum load lies at around 7500 kW.

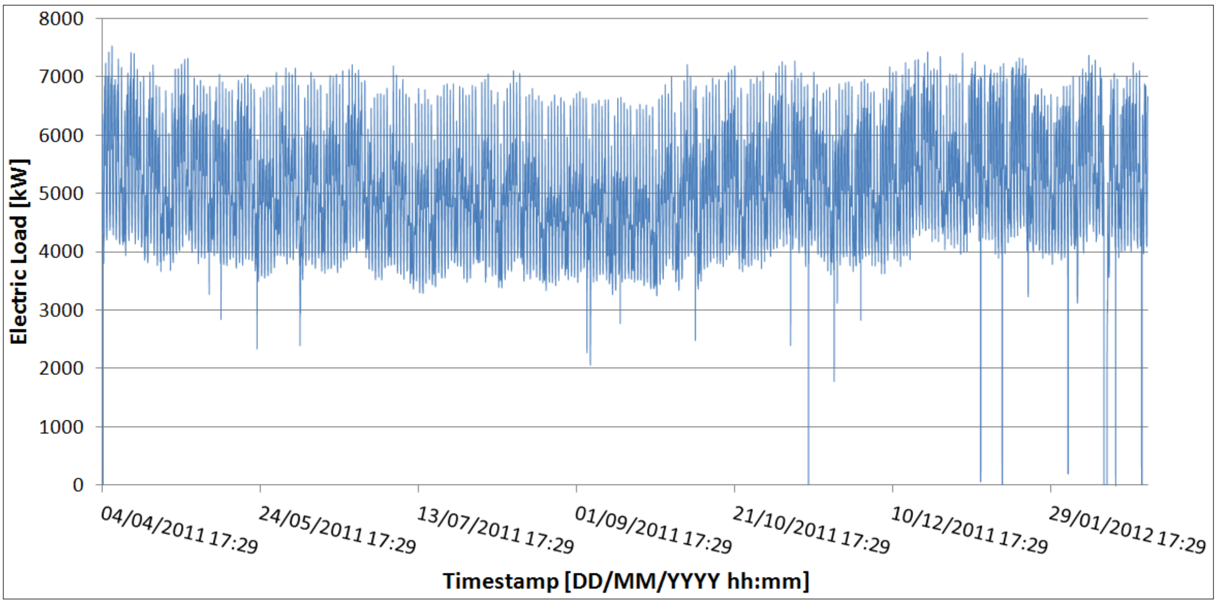


Figure 44 Half-hourly electric load curve of Tongatapu from April 2011 to February 2012

As no significant change in the minimum electric load seems to have occurred, the maximum installed wind power recommended by GHD is considered adequate for the purpose of this study. However, Tongatapu's current situation was not a scenario modeled by GHD. In July 2012, the 1 MW Popua Solar Farm started operating (Meridian Energy, n.d.). Additionally, several smaller grid-connected PV generators with a total nominal power of 28 kW have been installed and projects of similar size are in the planning stage (Eidt, 2012). Nevertheless, the scenario with a 2.1 MW PV generator capacity has not been reached.

Therefore, a proposed wind farm with a nominal power of 1.1 MW will be investigated within this study. This value is deduced from the selection of the wind turbine generator model as described in the next chapter.

5.2.2. Selection of the wind turbine generator model

When designing a wind farm, selecting a suitable wind turbine generator (WTG) is an important decision which directly influences the success of the project. WTGs differ greatly in nominal power, hub height, rotor diameter, environmental impact, mechanical load threshold, design concepts, availability and cost. The properties of the WTGs have to match the project characteristics, e.g. the wind resource, geographic location and power demand. Therefore, due care must be given to this step in the project.

However, utility scale wind turbines available to Tongatapu are limited to the products of a single manufacturer. As described in Chapter 3.3, Vergnet SA is the only company that is supplying wind turbines in suitable sizes and willing to ship and install products in the South Pacific. Vergnet has installed wind energy projects all over the world, including cyclone prone areas like New Caledonia, Fiji and Vanuatu.

Vergnet produces two different wind turbine models, one with a nominal power of 275 kW (GEV MP C) and one with a nominal power of 1 MW (GEV HP). Both turbines can be lowered and then secured on the ground in the event of a tropical cyclone. This is a necessary feature, because tropical cyclones can cause significant damage to wind turbines that are not adequately secured (see Chapter 3.3).

Figure 45 shows how the 275 kW GEV MP C is tilted to the ground using a gin pole. Apart from cyclone protection, the tilting design allows the turbine to be installed with a forklift truck rather than a heavy crane (Vergnet, 2008). Additionally, maintenance can be performed on the ground.

Figure 45 Tilting the Vergnet 275 kW GEV MP C wind turbine generator via gin pole (Vergnet, 2008)

Potentially, both turbine models mentioned above are available and suitable for cyclonic areas. However, using several 275 kW turbines will result in a smoother power output than using a single 1 MW turbine. “Under ideal conditions, the percentage variation of power output will drop as $n^{-\frac{1}{2}}$, where n is the number of wind generators. Hence, to achieve a significant smoothing effect, the number of wind turbines within a wind farm does not need to be very large.” (Ackermann, 2005).

According to this statement the power output variation of four 275 kW is 50 % lower in comparison to the power output variation of one 1 MW turbine. This assessment is based on the Equation 5.7 and 5.8 below. Therefore, this study will propose a wind farm consisting of four Vergnet 275 kW GEV MP C wind turbine generators with a total nominal capacity of 1.1 MW.

Percentage of power output variation of one wind turbine generator:

$$1^{-\frac{1}{2}} = 1 \ = 100\ \% \qquad 5.7$$

Percentage of power output variation of four wind turbine generators:

$$4^{-\frac{1}{2}} = \frac{1}{2} \ = 50\ \% \qquad 5.8$$

The GEV MP C is a two-bladed downwind turbine with a hub-height of 55 m and a rotor diameter of 32 m. A summary of the technical description can be found in Appendix 17. The GEV MP C was designed to meet the standards requirement described in the IEC 61400-1 ed. 2 (Vergnet, 2004) although the turbine has not been certified by an independent entity. Nevertheless, Vergnet advised that the turbine meets the turbulence thresholds required by a category B turbine.

A wind turbine generator built in accordance with IEC 61400-1 has a design lifetime of 20 years. Since turbulent winds cause mechanical stress, exceeding the turbulence values defined in the standard can decrease the turbine lifetime. As described in Chapter 4.1.3, the turbulence intensity characteristic for the Tongatapu wind regime can be derived from the data collected during the Lapaha wind monitoring campaign. According to IEC 61400-1 ed. 2 the characteristic turbulence intensity threshold for a class B turbine is defined by Equation 5.9:

$$TI_{max} = \frac{I_{15}(V_{ref} + 3\,V_{hub})}{4\,V_{hub}} \qquad 5.9$$

TI_{max} = Maximum permissible turbulence intensity
V_{ref} = Reference wind speed = $15\,\frac{m}{s}$
I_{15} = Reference turbulence intensity = 0.16
V_{hub} = Wind speed at hub height

Figure 46 plots the threshold Equation 5.9 in red. The characteristic turbulence intensities measured during the Lapaha wind monitoring campaign at 50 m agl and at 40 m agl are plotted in green and purple respectively. At 50 m agl the turbulence exceeds the permissible limit when wind speeds reach 17 m/s and beyond. Typically, the turbulence intensity decreases with increasing height. This is the case here, as higher turbulences were recorded at 40 m agl than at 50 m agl. Therefore, the turbulence encountered at the relevant turbine hub height of 55 m agl can be expected to be less severe than the values depicted here.

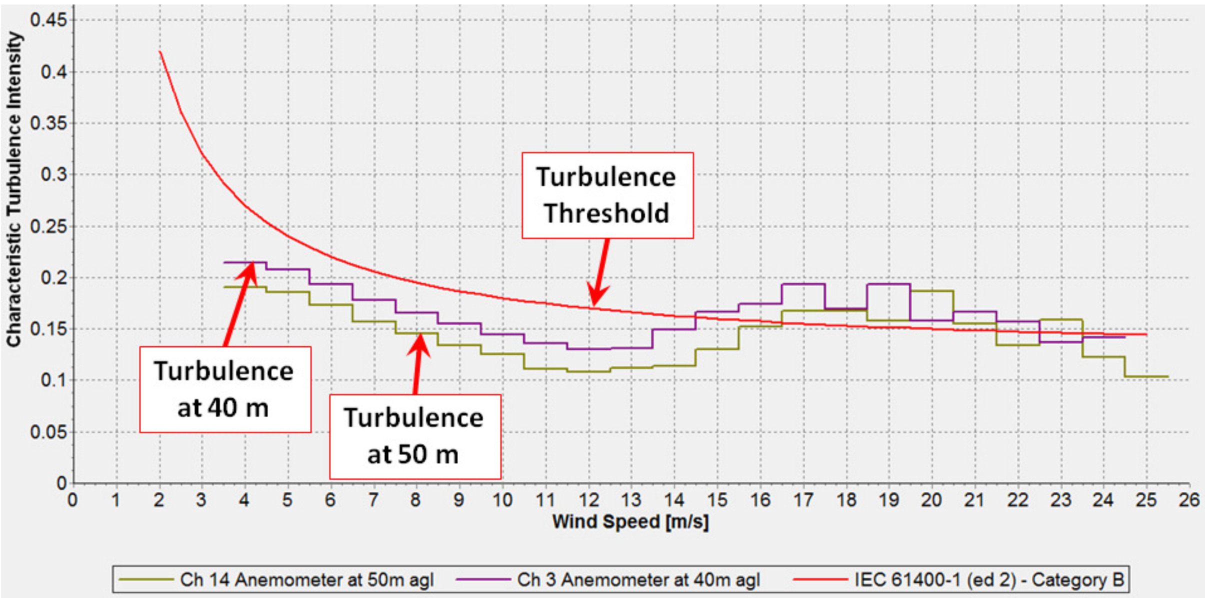


Figure 46 Turbulence intensity measured at Lapaha in comparison to IEC 61400-1 ed. 2 class B threshold

Additionally, wind speeds rarely reach 17 m/s and beyond. Out of the 91,874 ten-minute wind speed measurements collected during the Lapaha campaign, only 133 measurements were recorded at or above 17 m/s. This small sample is not sufficient to accurately assess the turbulences that occur at high wind speeds. As the Lapaha wind monitoring campaign is still in operation at this time, a larger sample will be available in the future. A full feasibility study following this pre-feasibility study shall therefore assess the applicability of a class B turbine in more detail. Nevertheless, the 275 kW Vergnet GEV MP C wind turbine generator will be considered suitable for the assessment conducted in this study.

5.2.3. Selection of wind turbine generator locations

Selecting appropriate locations for wind turbines is of great importance to maximize energy yields. Nevertheless, many different factors need to be taken into account to make an appropriate decision. The wind farm layout proposed by this study is shown in Figure 47, while the geographical coordinates are listed in Table 12. The elevation is interpolated from the digital elevation model. The criteria determining the selection of the wind farm layout are described in detail below.

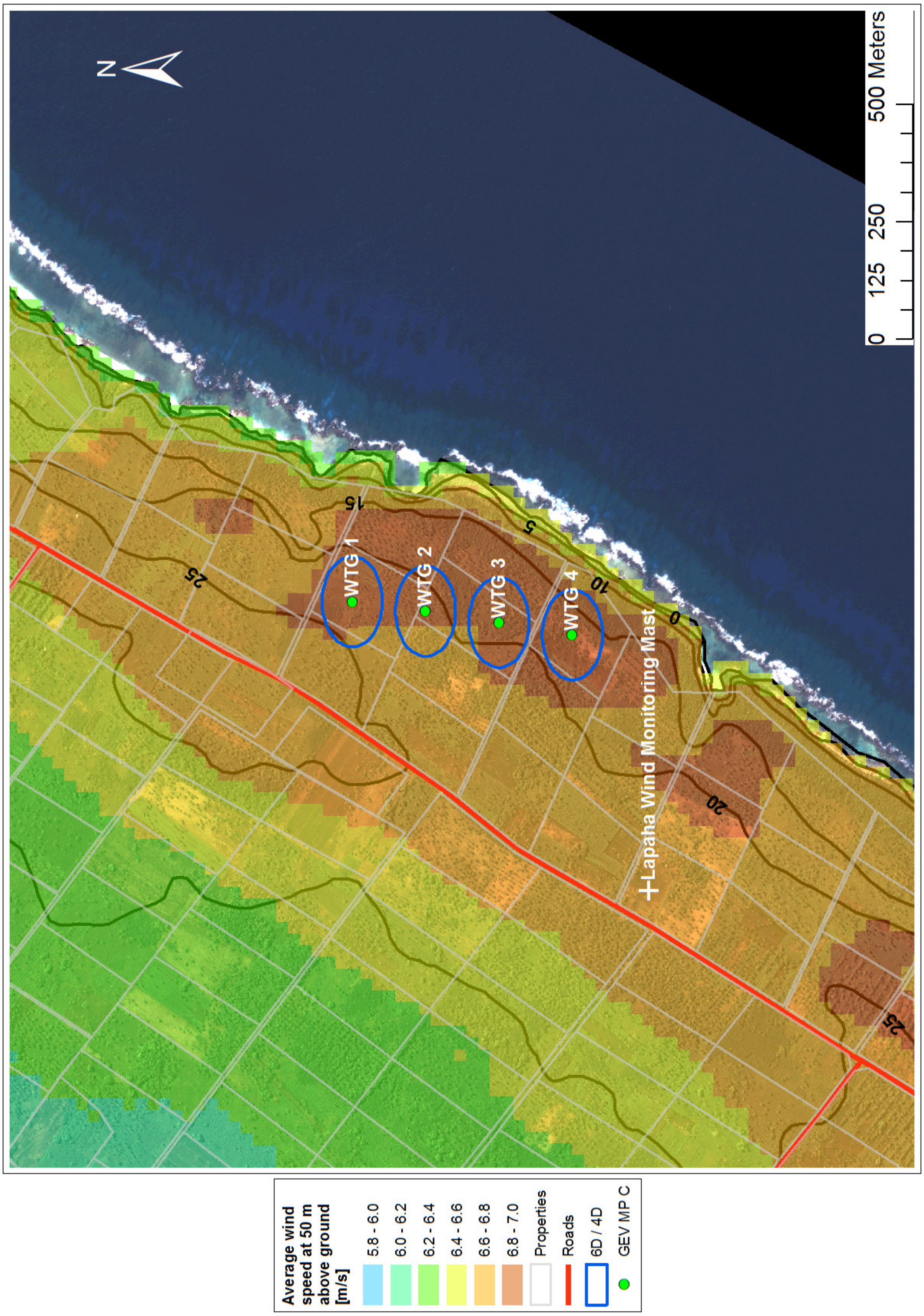


Figure 47 Map of proposed wind farm layout

Table 12 Geographical coordinates and elevation proposed wind turbine generator locations

Label	Latitude [°]	Longitude [°]	Elevation [m]
WTG 1	-21.183568°	-175.087185°	22.9
WTG 2	-21.184970°	-175.087359°	20.6
WTG 3	-21.186382°	-175.087572°	19.4
WTG 4	-21.187793°	-175.087814°	16.6

The wind turbine generator locations were selected in accordance with the following criteria:

1. Criterion: Wind turbine generators need to be located in close proximity to the Lapaha wind monitoring mast.

Initially, Tonga Power Limited stated that a wind farm should be located at the north eastern cape of Tongatapu. This preference was based on the high wind speeds determined by Vergnet's wind mapping study as well the availability of the electric grid at that position. Figure 48 shows the location of Tongatapu's high voltage (11 kV) distribution grid. TPL stated that the north eastern feeder would be upgraded in the near future as part of a separate project. This distribution line would then be able to sustain a 1 MW wind farm and transport the power to Nuku'alofa where the highest electric loading occurs.

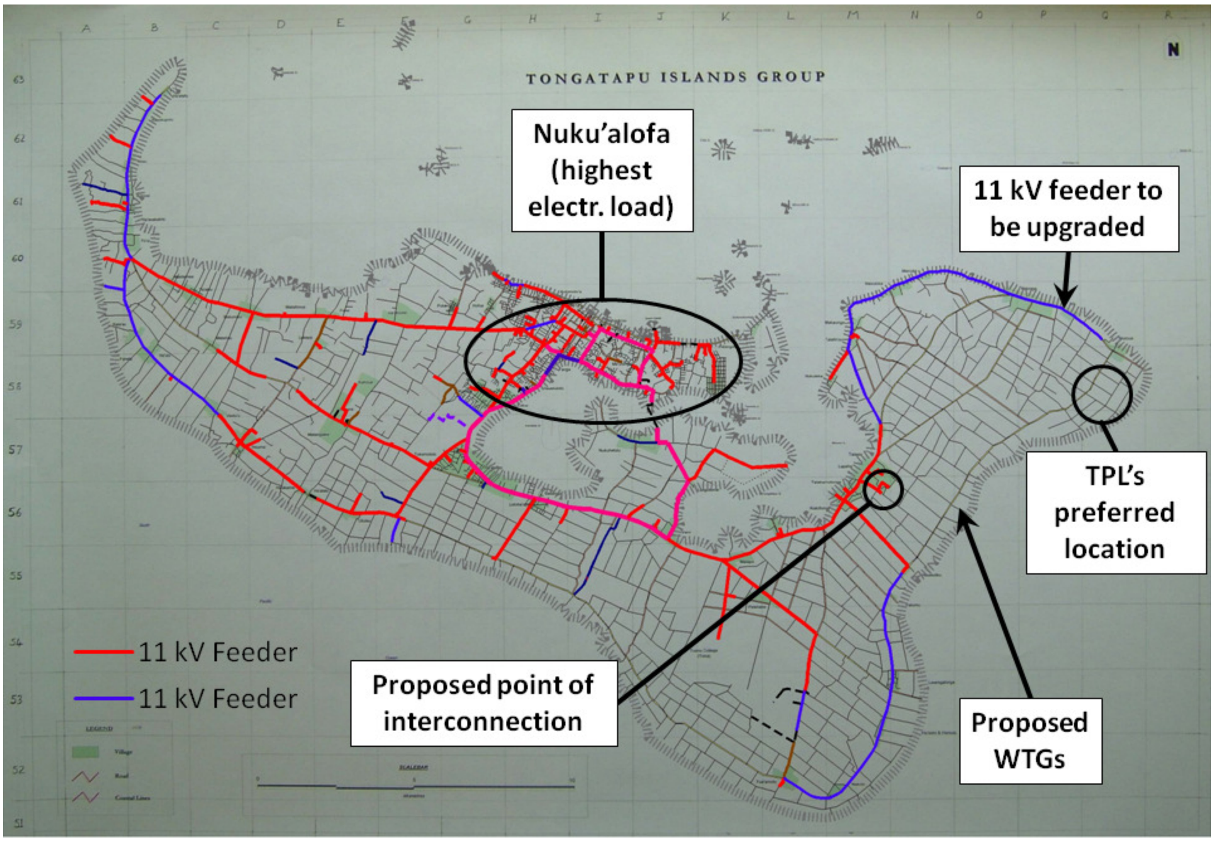


Figure 48 Map of Tongatapu's electricity transmission grid (TPL, 2012)

Nevertheless, the Tongan Ministry of Environment and Climate Change requested to assess proposed wind turbine generators close to the Lapaha wind monitoring mast. A major advantage of modeling a wind farm at this location is the higher level of certainty the WAsP model provides in close range to the point of measurement. Furthermore, Figure 47 shows that average wind speeds in this area reach between 6.8 m/s and 7.0 m/s. These values are not significantly lower than those encountered on the north eastern cape of the island. Additionally, the proposed point of interconnection will shorten the distance to the major electricity consumers. Therefore, the proposed wind turbine generators were placed in accordance with the Ministry's request.

2. <u>Criterion:</u> Wind turbine generators need to be located in areas with high wind speeds.

As shown in Figure 47, all proposed WTG locations lie within the highest wind speed area close to the wind monitoring mast. The positions are a compromise between placing turbines close to the shore for maximum wind exposure and placing them at higher elevations further inland to reach greater wind speeds present at higher altitudes.

Furthermore, the thick brush directly lining the shoreline is assumed to serve as a protective barrier against erosion. As wind turbine construction entails clearcutting vegetation, locations outside of this area were chosen.

3. <u>Criterion:</u> Wind turbine generators need to be located away from villages and houses to minimize shadow flicker and noise impact.

Shadow flicker and noise emitted from wind turbines are significant disturbances to neighboring residents. Shadow flicker is caused by the rotating wind turbine blade shading an observer for fractions of a second. Noise is emitted from the wind turbine as the rotor whirls through the air. The blade tips reach high speeds causing a constant sound pollution.

Placing wind turbines away from dwellings is the best option to limit these impacts. Figure 49 shows the WTG positions in reference to a single house located south of the Lapaha mast as well as the town located west of the wind turbines. Although the wind farm was placed well away from any dwellings, shadow flicker and noise emissions will be quantified in Chapter 5.2.4 in order to ensure that recommended values are not exceeded.

Figure 49 Satellite image showing the wind turbine generator locations in relation to relevant dwellings (Google Earth, 2012b)

4. Criterion: Wind turbine generators need to be located perpendicular to the main wind direction.

Wind turbines extract kinetic energy from air flowing through the rotor swept area. Therefore, the wind speed behind the wind turbine drops significantly. Additionally, the rotor induces turbulence into the airflow behind it. A turbine which is located downwind of another turbine will therefore suffer from decreased power output and increased fatigue.

In order to minimize this adverse effect, wind turbines are aligned perpendicular to the main wind direction. As the wind blows from the east 25 % of the time (see Figure 34) the wind turbines shall be aligned north to south.

5. Criterion: Wind turbine generators need to be located at a minimum distance from each other of 4 x rotor diameter.

In large wind farms, the space between wind turbine generators is generally assigned to be a minimum of 6 to 7 times their rotor diameter in main wind direction and 3 to 4 times their rotor diameter perpendicular to the main wind direction. This criterion depends on the shape of the wind rose and the turbine manufacturer's specifications.

For the wind farm proposed in this study, the distances chosen are 6 times rotor diameter in main wind direction and 4 times rotor diameter perpendicular to main wind direction. The latter was selected to be 4 rather than 3 in order to ensure that turbulence from neighboring turbines is minimized. These minimum distances are represented by the blue ellipse surrounding the base of the turbine (see Figure 47 above).The major axis (east to west) is 6 X Rotor Diameter = 192 m. The minor axis (north to south) is 4 X Rotor Diameter = 128 m. The blue ellipses may not intersect each other.

6. Criterion: Wind turbine generators need to be located relatively close together.

Constructing wind turbines relatively close together minimizes balance of plant works such as grid and road connections. Although placing the turbines in different locations all over the island has benefits in terms of power quality and grid loading, the high costs do not warrant such an approach.

The final layout shown in Figure 47 above was produced using all six criteria listed in this chapter. The layout was submitted to the Ministry of Environment and Climate Change and preliminary approval was granted. All further predictions concerning annual energy production, noise, shadow flicker and all economic analyses will be based on the layout presented in this chapter.

It is important to note that several aspects influencing the final placements of the turbines could not be considered in this study. In addition to the criteria mentioned above, a full feasibility study will need to investigate the following items in detail:

- Grid connection
- Land availability
- Environmental impacts
- Geological suitability
- Archeological relevance of the construction zone
- Risks associated with bird and bat strike
- Aviation routes
- Microwave radio paths

The final wind farm layout will then need to be modified accordingly.

5.2.4. Quantifying noise and shadow flicker

As mentioned in the previous chapter, the impacts of noise and shadow flicker emitted by wind turbines must be minimized. Therefore, the turbines need to be located far enough away from dwellings to sufficiently reduce these adverse effects to acceptable levels. In this context, the single house south of the Lapaha wind monitoring mast is of particular concern, because it is located only 970 m from WTG 4.

Shadow flicker is easily quantified in WindPRO, because it merely depends on the turbine's height and rotor diameter, the terrain elevation and the path of the sun. Figure 50 shows which locations are subject to how many hours of shadow flicker per year. The graphic depicts iso-lines meaning that every point on the line is subject to exactly 100, 30, 10 or 0 hours of shadow flicker per year. Note that the values calculated represent the worst case scenario. This means that the calculation assumes clear skies every day of the year. As shadow flicker does not occur during cloud cover, actual values will be lower than those presented here.

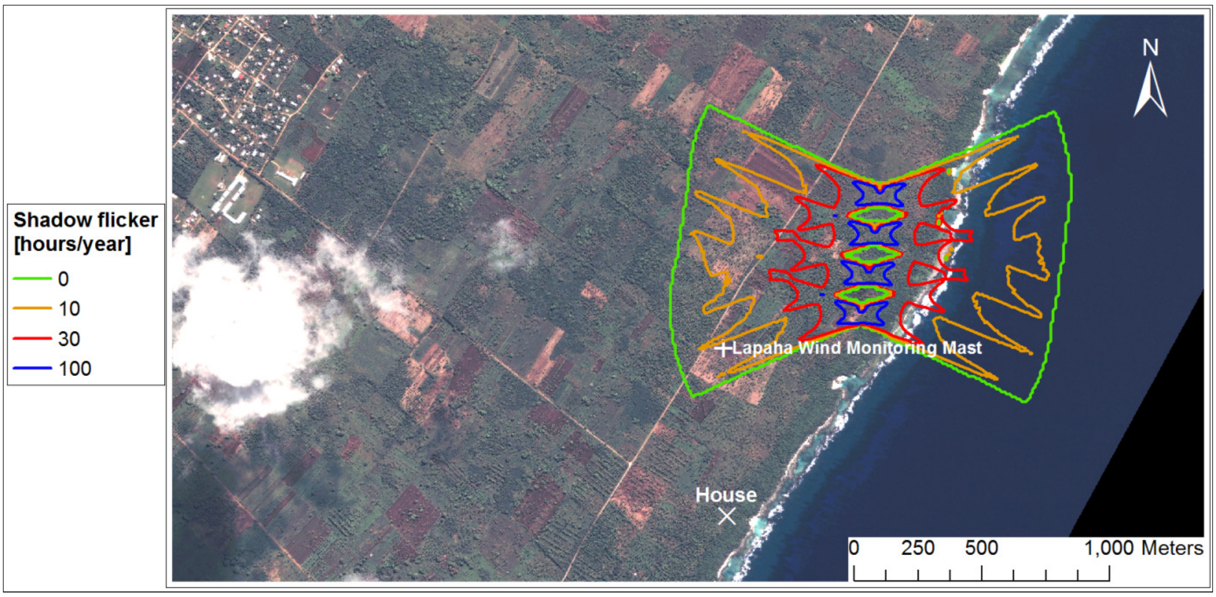


Figure 50 Worst case scenario of locations subject to yearly shadow flicker

As can be seen in the graphic above, neither the single house in the south nor the town to the west of the turbines are subject to any shadow flicker. This impact is therefore not of concern.

When quantifying noise emission, however, the calculation becomes more complex because it is dependent on a number of variables. For example, the regulations of some countries demand taking ambient noise into account, while others disregard ambient noise and merely compare turbine noise to a set threshold. The latter procedure will be employed by this study, because ambient noise measurements are not available.

No information on noise emission of the GEV MP C wind turbine was provided by Vergnet. Therefore, noise predictions cannot be performed for the full range of operating wind speeds. Only the sound pressure level at reference wind speed (8 m/s) could be obtained from a noise impact report prepared for the Butoni wind farm in Fiji, which happens to use the GEV MP C. Consequently, the noise level predictions must be treated as indicative only.

The report states that the sound pressure level of the turbine was measured at 105 dB(A) at the wind speed of 8 m/s (Marshall Day Acoustics, 2005). Although noise levels emitted differ with wind speed, 8 m/s are considered the reference wind speed. Higher wind speeds incur higher ambient noise levels which in turn makes the wind turbine generator less noticeable. Therefore, noise levels modeled at 8 m/s will be considered a sufficient indicator for the purpose of this study.

The report defines an acceptable level of sound power level to be 40 dB(A) at any dwelling: "The level of 40 dBA has been based on the World Health Organisation guidance for an accepted indoor level of 30 dBA, and assumes a reduction from outdoors to indoors of typically 10dB with open windows" (Marshall Day Acoustics, 2005). However, the GEV MP C produces an audible tone of 300 Hz. Therefore, the report suggests imposing a 5 dB penalty which is in line with standard NZS 6808 used in New Zealand. Therefore, a sound pressure level threshold of 35 db(A) is defined acceptable for the single house located south of the Lapaha wind monitoring mast.

In terms of predicting noise emission from wind turbine generators, different countries use different methods of calculation. However, EMD states that the international standard DIN ISO 9613-2 can be used as a general approach (EMD, 2012d). The method is implemented into WindPRO and described in detail in (EMD, n.d.). The results of the calculation are depicted in Figure 51.

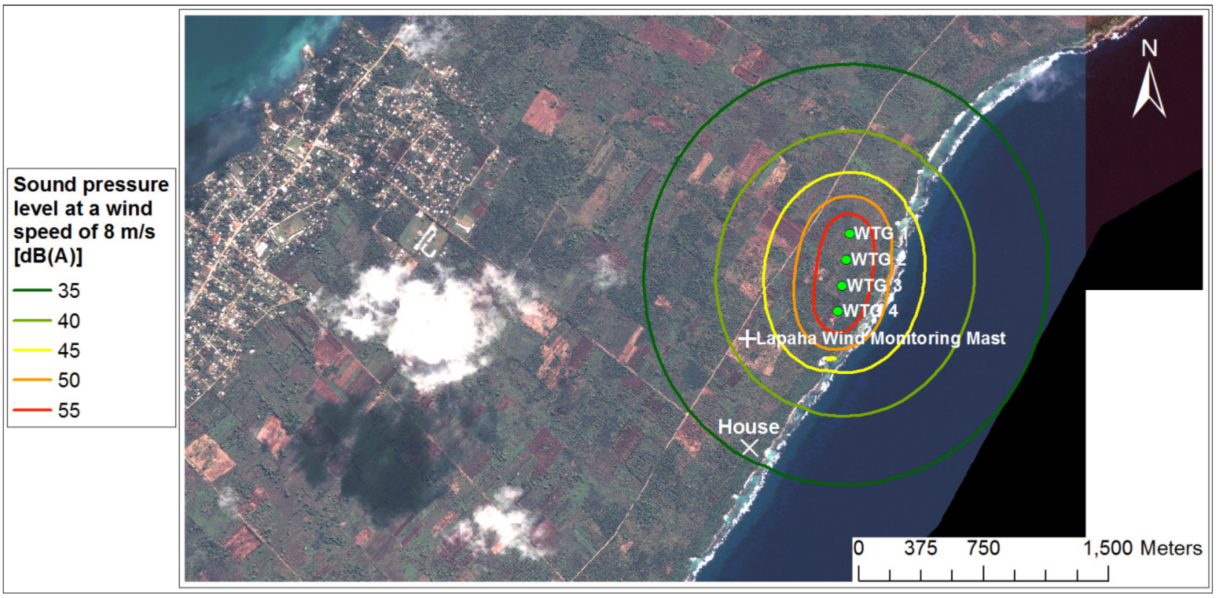


Figure 51 Sound pressure levels surrounding the wind turbine generators at a wind speed of 8 m/s

The image above shows that noise radiates spherically around the turbine locations. The iso-noise lines represent sound pressure levels at the reference wind speed of 8 m/s. While the town to the west of the turbines is well outside the area of concern, the model predicts a sound pressure level of 36 dB(A) at the single house. This value slightly exceeds the threshold value. However, the noise calculation model does not take the thick vegetation into account. The brush and high trees will further reduce noise levels. Additionally, the values here must be treated as indicative only. Therefore, the wind farm layout presented in the previous chapter will be considered suitable for the purpose of this study.

5.2.5. Turbine installation and balance of plant works

A preliminary plan of the necessary balance of plant works for the proposed turbine locations will be presented in this chapter. Balance of plant refers to those works that are not directly related to the construction of the wind turbine generators but are necessary to install or operate them. Balance of plant works therefore include the extension of the electric distribution grid, interconnection of the turbines to the electrical substation and construction of the latter, building or widening roadways, and civil works at the turbine site.

In order to visualize some of the works necessary, Figure 52 shows the 3 MW wind farm in Vanuatu as an example. The project was implemented in 2009 and comprises eleven 275 kW Vergnet GEV MP C wind turbine generators.

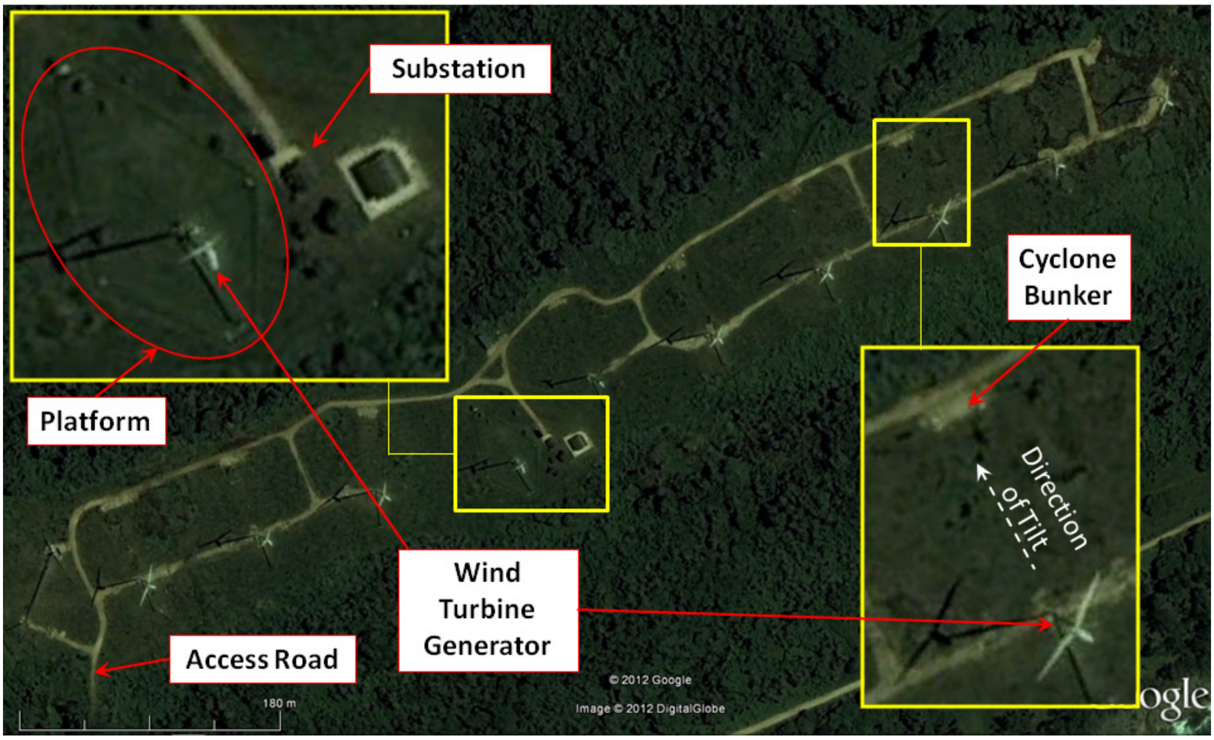


Figure 52 Satellite image of the Vanuatu wind farm (Google Earth, 2012a)

All large vegetation has been cleared from the project area and an access road leads from the main road to each wind turbine and the substation. The substation is located in the center of the wind farm. Each wind turbine is located in the center of a kite-shaped platform. The turbine's guy wires are anchored to the ground within the corners of the platform.

The elongated corner of the platform holds the cyclone bunker. The cyclone bunker protects the nacelle and blades of the turbine while the turbine is in tilted position (see Figure 53). In case of a cyclone, the wind turbine is tilted, the rotor blades are secured to the ground and the turbine's mast rests on the tower support. Securing a single wind turbine takes a two man crew "less than an hour time" (Vergnet, 2008).

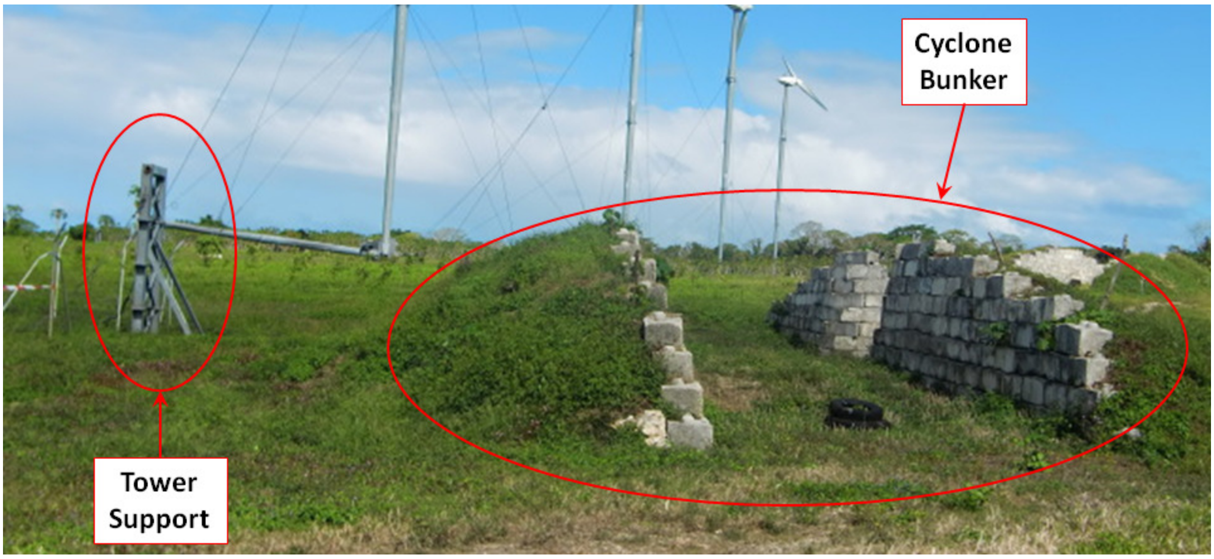


Figure 53 Cyclone bunker and stand used when the wind turbine generator is tilted to the ground

For the purpose of estimating costs for the balance of plant works, a preliminary layout for road and grid connection is presented in Figure 54. This layout will allow an estimation of the distances that will need to be covered in order to connect the Tongatapu wind farm to the public road and the electric distribution grid.

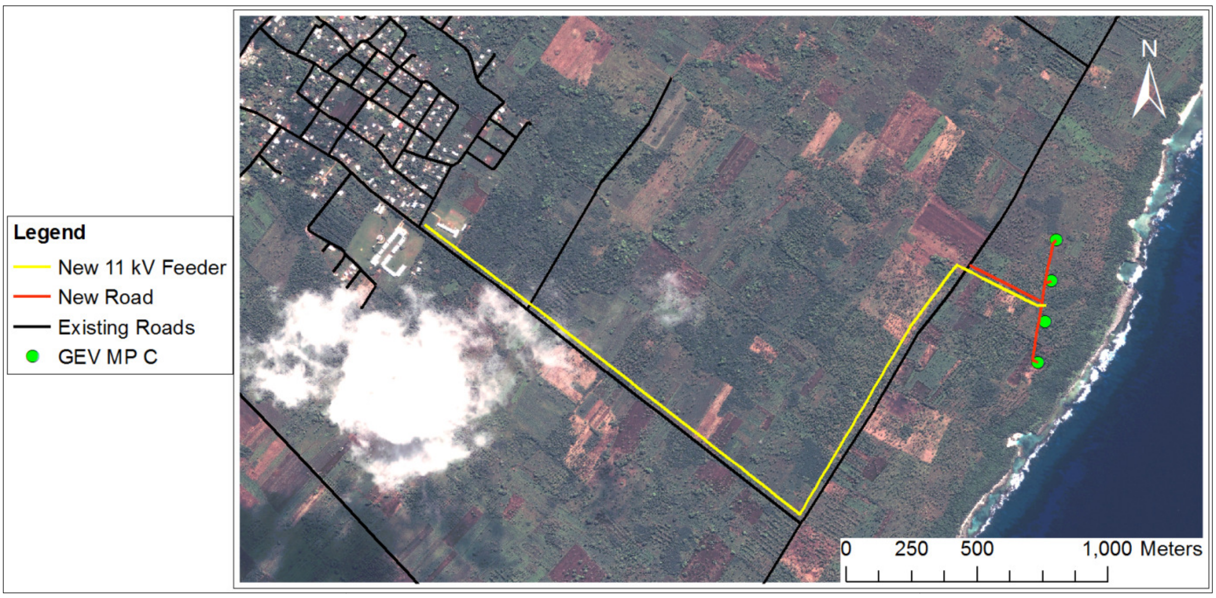


Figure 54 Sketch of road and grid extension necessary to install and operate the Tongatapu wind farm

As shown above, a new 11 kV feeder will need to extend from the town east of the wind turbines to the substation located in the center of the wind farm. The feeder shall be constructed alongside the new and the existing road and extend a total distance of approximately 3400 m. A new road would need to extend approximately 800 m from the existing road to each wind turbine.

5.2.6. Calculation of annual energy production and capacity factor

With the wind resource known and using the proposed turbine locations, the annual energy production (AEP) of the Tongatapu wind farm can be estimated accurately. In order to calculate energy production, the wind speed distribution is multiplied with the power curve of the wind turbines to render the gross energy output. However, a number of losses need to be accounted for in order to quantify the more realistic net energy output. The net energy is then used to evaluate the wind farm’s capacity factor (CF), which is a key figure in measuring the wind farm efficiency. Additionally, the diesel fuel savings can be projected based on the net energy produced by the Tongatapu wind farm.

The wind speed distribution used for assessing the energy output in this chapter shall be based on the long-term corrected wind resource compiled in the wind resource assessment (see Chapter 4.3). Since the resource was assessed for the location and the height of the measurement mast only, the data needs to be horizontally extrapolated to the wind turbine locations and vertically extrapolated to the turbine hub height of 55 m agl. This operation is performed by the WAsP model in the same manner as was done in the production of the wind resource map (see Chapter 5.1). The WAsP model produces a wind statistic for each turbine location. All four location specific wind statistics are then multiplied with the power curve data of the turbine.

The power curve is a wind turbine generator model specific set of information which expresses the power output as a function of wind speed. The power curve of the GEV MP C was provided by Vergnet but the document states that the data was measured by DEWI, the German Wind Energy Institute (Vergnet, 2009). As DEWI is an independent institute using accredited measurement procedures, the power curve data can be regarded as accurate.

The plot in Figure 55 shows that the turbine starts power production at 4 m/s (cut-in wind speed), reaches nominal power of 275 kW at 12.5 m/s and stops power production when wind speeds exceed 20 m/s (cut-out wind speed). The data table is listed in Appendix 18.

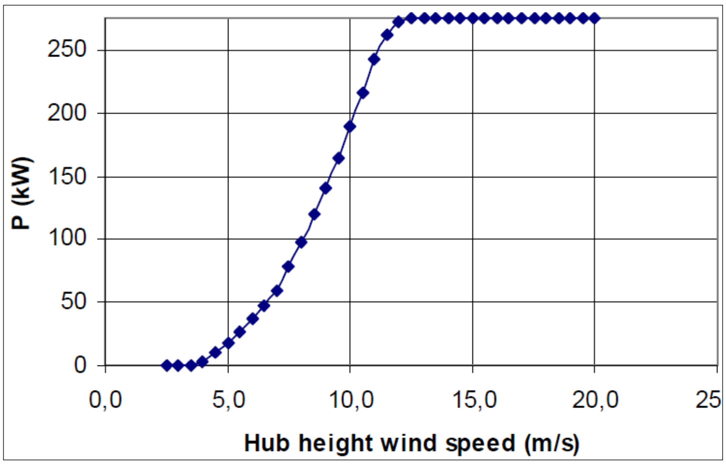


Figure 55 Power output as a function of wind speed at an air density of 1.225 kg/m³ (Vergnet, 2009)

It is important to note that the power curve is air density dependent and the measurement was conducted at standard air density of 1.225 kg/m³. This value is derived from standard sea-level conditions where air pressure is 101325 Pa and air temperature is 15° C while relative humidity is 0 %. As power output decreases with decreasing air density, the values need to be adjusted to Tongan conditions to avoid over-estimation of power output.

The Lapaha wind monitoring campaign measured a mean temperature of 24°C. Humidity and air pressure data was not recorded by the measurement and will therefore be neglected. As humidity has only a minor influence on air density and the turbines are located not far above sea level, neglecting these factors is not considered relevant. The air density shall therefore be calculated as defined by Equation 5.10:

$$\rho = \frac{P}{RT} \qquad 5.10$$

ρ = Air density (kg m^{-3})
P = Air pressure (101325 Pa)
R = Specific gas constant for dry air (287 J/kgK)
T = Air temperature (24°C = 24 K + 273.15 K = 297.15 K)

The calculation above results in an air density of 1.188 kg/m³ which is a reduction of 3 % relative to standard conditions. The power curve used in the energy calculation presented in this chapter is adjusted to take the reduction into account. It is not possible to merely reduce all power output values in the power curve by 3 %, as this would reduce the rated power of the turbine. However, WindPRO is capable of performing the adjustment as described in (Svenningsen, n.d.). The resulting adjusted power curve data is listed in Appendix 19.

Multiplication of the turbine height and location specific wind resource with the air density adjusted power curve results in gross energy output listed in Table 13. The table shows that the WAsP model predicts a mean wind speed of 6.9 m/s at the hub height of 55 m agl for all wind turbine generators. The total gross energy output of the wind farm is quantified at 2921.4 MWh per year.

Table 13 Gross energy production of the Tongatapu wind farm

Generator label	**Gross energy production [MWh/year]**	**Mean wind speed at hub height [m/s]**
WTG 1	730.9	6.9
WTG 2	729.1	6.9
WTG 3	729.1	6.9
WTG 4	732.4	6.9
Total	**2921.4**	6.9

It is important to note that the gross energy output will not be achieved by the wind farm because it is reduced by a number of factors. The more realistic net energy output is calculated by making appropriate deductions:

1. <u>Deduction:</u> Wake effect

The power output of a wind farm is reduced by the shadowing effect of wind turbine generators that are located close to each other. A turbine that is downwind of another turbine will be subject to decreased wind speed. WindPRO allows quantifying the energy losses induced by this effect through using the N. O. Jensen model described in (EMD, 2012a). The basic principle of the model is shown in Figure 56.

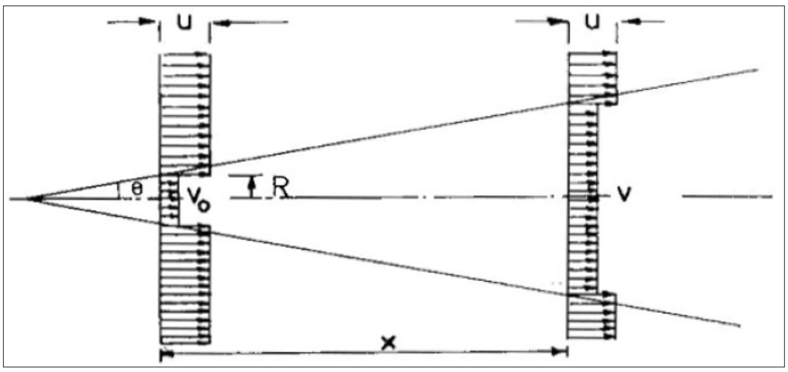


Figure 56 Basic principle of the N. O. Jensen model (EMD, 2012a)

The free flowing wind speed u is decelerated by the rotor radius R to become v_0. The downwind turbine located at distance x will be subject to the reduced wind speed v which is dependent on the widening of the shadow cone. “The wake decay constant is a measure of the down-stream widening of the shadow cone, […] varying from 0.04 for a roughness class of 0, to 0.1 for a roughness class of 3. The use of the default value of 0.075 for all calculations on land is judged to have only marginal impact on the results” (EMD, 2012a). Therefore, the default wake decay constant is used below to predict the energy output after wake losses have been deducted.

The wake reduced energy output is listed in Table 14. Wake reductions are below 1 % on average. This low value was expected, because the wind turbines are spaced fairly far apart and all turbines are located in a single row perpendicular to the main wind direction. The total wake reduced energy output of the wind farm is therefore quantified at 2896.2 MWh per year.

Table 14 Wake reduced energy production of the Tongatapu wind farm

Generator label	Gross energy production [MWh/year]	Wake reduced energy production [MWh/year]	Wake reduced efficiency [%]
WTG 1	730.9	728.6	99.7
WTG 2	729.1	721.8	99.0
WTG 3	729.1	720.7	98.9
WTG 4	732.4	725.1	99.0
Total	**2921.4**	**2896.2**	**99.1**

2. <u>Deduction:</u> Losses

In order to assess power output realistically, a number of losses need to be taken into account. However, the loss reductions imposed here will be limited to the most important loss factors for which EMD provides guidelines, i.e. turbine availability and electrical losses (EMD, 2012a).

It should be noted that many loss factors can reduce the energy output. Examples are losses due to off-yaw axis wind, performance degradation, shutdown due to extreme events, high wind hysteresis etc. A more complete list of losses can be found in *WindPRO 2.8 Manual: Energy - Loss and Uncertainty* (EMD, 2012b). However, these factors will be neglected here, because data was not available to allow accurate calculation of these losses.

The wind turbine availability is limited because performing maintenance requires shutting down the device. EMD states that "modern WTGs have availability losses of approximately 3-5%" (EMD, 2012a). The anticipated availability loss factor shall be 5% for the GEV MP C wind turbine, as the location is rather remote and maintenance crew response times may therefore be high in comparison to European wind farms.

Some electrical losses must be accounted for because "the power curve is typically measured before the transformer losses. Grid losses will typically be round 2% including the transformer, where 1% typically are lost in the build-in step-up transformer" (EMD, 2012a). The losses of 2 % mentioned here only include electrical losses from the low-voltage side of the wind turbine generator to the substation. All total power output figures presented henceforth shall therefore be considered at the point of the Tongatapu wind farm substation. The net energy production which includes the wake, availability and electrical loss reduction is listed in Table 15.

Table 15 Wake and loss reduced net energy production of the Tongatapu wind farm

Generator Label	Gross energy production [MWh/year]	Wake reduced efficiency [%]	Turbine availability [%]	Electrical efficiency [%]	Net energy production (P50) [MWh/year]
WTG 1	730.9	99.7	95	98	678.3
WTG 2	729.1	99.0	95	98	672.0
WTG 3	729.1	98.9	95	98	671.0
WTG 4	732.4	99.0	95	98	675.1
Total	**2921.4**	**99.1**	**95**	**98**	**2696.4**

It is important to point out that the total net energy production of 2696.4 MWh per year is denoted as the P50 value. The 'P' stands for probability because the P50 net energy production has a 50 % probability of exceeding and a 50 % probability of not reaching the value presented here.

In order to obtain funding for a wind energy project, the P90 value is usually presented to the financiers. The P90 value is that amount of energy which will be produced by the wind farm with a probability of 90 %, thus reducing the economic risk. In order to calculate this value, all uncertainties need to be quantified to obtain the standard deviation. According to EMD, uncertainties result from the wind data measurement, the long-term correction, the WAsP model and the power curve (EMD, 2012a). While a full feasibility study will need to quantify the P90 value, time constraints do not permit evaluating the uncertainties within the scope of this study. Therefore, all further technical and economic assessments will be based on the P50 net energy production presented in Table 15 above.

As mentioned previously, the capacity factor (CF) is a key figure in measuring a wind farm's efficiency. It is dependent on the net energy production and the turbine's rated power. The capacity factor is defined as noted in Equation 5.11:

$$CF = \frac{Net\ Energy\ Production}{365\,\frac{days}{year} \cdot 24\,\frac{hours}{day} \cdot Rated\ Power} \qquad 5.11$$

As listed in Table 16, the Tongatapu wind farm is expected to achieve an average capacity factor of 28 % when the net annual energy output of 2696.4 MWh is reached.

Table 16 Net annual energy production and capacity factor of the Tongatapu wind farm

Generator Label	Net energy production (P50) [MWh/year]	Capacity factor (P50) [%]
WTG 1	678.3	28.2
WTG 2	672.0	27.9
WTG 3	671.0	27.9
WTG 4	675.1	28.0
Total	**2696.4**	**28.0**

5.2.7. Calculation of potential diesel fuel savings

In order to compare the economic feasibility of this wind energy project, potential diesel fuel savings need to be quantified. Electricity produced by the wind farm will be given priority over electricity produced by Tongatapu's diesel power station. Therefore, the gross production of the diesel power station will be reduced by the amount of energy equivalent to the net production of the wind farm. This is based on the assumption that electricity from both power stations would experience the same amount of distribution losses in the electric grid.

The diesel generators operating alongside the wind farm will experience reduced fuel efficiency, because fuel consumption does not decrease linearly with power output. A diesel generator will need to operate constantly under low or fluctuating load to meet the need for a spinning reserve. This is necessary, because the power output of the wind farm will fluctuate causing the need for instantaneous compensation by another power source.

Assessing the reduction in fuel efficiency accurately requires a sophisticated dynamic model. As this task cannot be performed within the limited scope of this study, a value will be estimated based on available research. Nevertheless, a full feasibility study will need to assess fuel efficiency reduction more accurately by simulating power output while taking the diesel generator specific efficiency curve into account.

In a project similar to Tongatapu, a 2 % fuel efficiency reduction was adopted by a wind power project evaluation prepared for the Cook Islands (Cheatham & Zieroth, 2002). Although the document does not state whether the efficiency reduction was modeled, the 2 % value will be treated as indicative.

The study evaluated a proposed 1.8 MW wind farm. However, the load curve of the island varied from only 1500 kW to 3500 kW. The rated power exceeds the minimum electric load, causing the spinning reserve diesel generator to operate without load at times of high wind speeds and low demand. The fuel efficiency reduction can therefore be expected to be less in the case of Tongatapu. Therefore, an estimated 1.0 % fuel efficiency reduction in Tongatapu’s diesel power station will be assumed adequate, considering that the 1 MW solar farm and the 1.1 MW wind farm both represent fluctuating power generators.

In order to calculate fuel savings, two different scenarios need to be analyzed. Electricity production and fuel efficiency data were only available for 2007 to 2011, a period where diesel generators were the only source of power. As mentioned in previously, a 1 MW photovoltaic generator started operation in July 2012. Although no up to date data is available, this fluctuating source of power is also expected to reduce fuel efficiency. Therefore, fuel savings need to be compared to the present solar/diesel scenario rather than the outdated diesel only scenario. This requires an assessment of the solar/diesel scenario first, which then enables predictions concerning the wind/solar/diesel scenario.

All calculations below are based on monthly electricity generation data of the Tongatapu diesel power station ranging from January 2007 to October 2011. Figure 57 shows that that the fuel efficiency was relatively constant with no significant trend, while monthly electricity production varied from 3.3 GWh to 4.4 GWh. The data is used as is and averages from that period serve as the baseline. Therefore, the average electricity production of the all diesel scenario amounts to 3,880,741 kWh per month while average fuel efficiency is 4.058 kWh per liter.

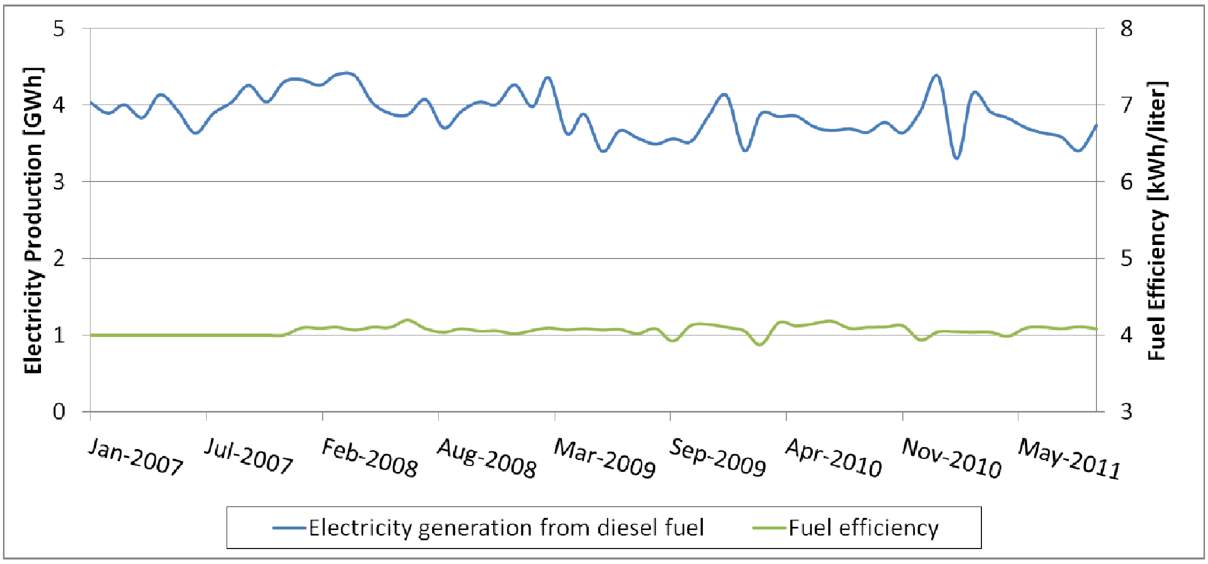


Figure 57 Diesel powered electricity production and fuel efficiency in Tongatapu from January 2007 to October 2011 (TERM-IU, 2012)

Based on these average values, the calculations listed in Table 17 are performed. The annual solar energy production is known to be 1,880,000 kWh per year. The anticipated fuel use of 11,011,694 liters per year in the solar/diesel scenario is based on a 0.5 % fuel efficiency reduction, as opposed to the all diesel scenario.

The annual wind energy production is predicted to provide a share of 5.8 % of gross electricity production. However, the fuel use is expected to decline by only 5.1 % in comparison to the solar/diesel scenario. This is caused by the fuel efficiency reduction of 1 % as opposed to the all diesel scenario. The total fuel savings incurred by the Tongatapu wind energy project will therefore amount to 559,887 liters annually in comparison to the solar/diesel scenario.

Table 17 Calculation of diesel fuel savings incurred by the Tongatapu wind farm

Scenario	Item	Var.	Source	Amount	Unit
Diesel generation (Jan 2007 to Oct 2011)	Average monthly electricity production	A	(TERM-IU, 2012)	3,880,741	kWh/month
	Average yearly electricity production	B	= A*12	46,568,891	kWh/year
	Average fuel efficiency	C	(TERM-IU, 2012)	4.058	kWh/liter
Solar and diesel generation	Annual solar energy production	D	(Meridian Energy, n.d.)	1,880,000	kWh/year
		E	= (D/B)*100	4.0	%
	Remaining energy demand	F	= B-D	44,688,891	kWh/year
	Fuel efficiency reduction	G	*)	0.50	%
	Anticipated fuel efficiency	H	= C*(100-G)/100	4.038	kWh/liter
	Anticipated fuel use	I	= F/C	11,011,694	liters/year
Wind, solar and diesel generation	Annual wind energy production	J	*)	2,696,362	kWh/year
		K	= (J/B)*100	5.8	%
	Remaining energy demand	L	= F-J	41,992,528	kWh/year
	Fuel efficiency reduction	M	*)	1.00	%
	Anticipated fuel efficiency	N	= C*(100-M)/100	4.018	kWh/liter
	Anticipated fuel use	O	= L/N	10,451,807	liters/year
	Fuel saved (as opposed to solar and diesel scenario)	P	= I-O	559,887	liters/year
		Q	= (1-(O/I))*100	5.1	%

*) based on assessments and assumptions described in this study

5.3. Summary of the technical and environmental assessment

The technical and environmental assessment uses the long-term adjusted wind resource to create a wind resource map of Tongatapu. The necessary digital land cover and elevation models required some modification to allow their use in the WindPRO software. Based on the assessment of the DEM as well as the site visit to the eastern coast it was concluded that the WAsP model is applicable for wind climate extrapolations in Tongatapu. The resulting wind resource map shows that mean wind speeds at 50 m agl reach between 7.0 m/s and 7.2 m/s on the eastern side of the island. The accuracy of the wind resource map is, however, limited by partially outdated terrain models and the WAsP model itself. Predictions are most reliable within close range of the Lapaha wind monitoring mast.

The wind resource map permitted choosing wind turbine generator locations for maximum energy yield. The designed wind farm layout with a total nominal generator capacity of 1.1 MW uses four Vergnet 275 kW GEV MP C wind turbines with tiltable towers. This allows strapping the nacelle to the ground to avoid damage in the event of a cyclone. Sizing the wind farm at 1.1 MW is based on dynamic models presented in a previous study.

Indicative noise and shadow flicker values of the selected wind farm layout are quantified. While shadow flicker does not impact any nearby dwellings, the noise model shows that a single house located 970 m from one of the turbines may slightly exceed recommended noise levels by 1 dB(A). As, however, thick brush and large trees are expected to reduce sound pressure levels beyond the projections of the noise model, the wind farm layout is deemed suitable in terms of noise and shadow flicker emissions.

The annual energy production of the wind turbine generators is calculated by extrapolating the long-term wind resource to hub height and location of each turbine using the WAsP model. The gross energy output is quantified, but appropriate deductions are made for air density reduction, wake effect, turbine availability and electrical losses. Therefore, the net energy production at the substation of the wind farm is predicted to be 2696.4 MWh per year, while the capacity factor is 28.0 %. As uncertainties were not taken into account in these projections, these numbers represent the P50 value. Consequently, the net energy production has a 50 % probability of exceeding and a 50 % probability of not reaching the value presented here.

Due to lack of recent fuel use and electricity generation data, the calculation of potential diesel fuel savings is done by modeling the current solar/diesel scenario. This was based on data recorded during the all diesel operation between 2007 and 2011. The solar/diesel scenario takes a 0.5 % and the wind/solar/diesel scenario takes a 1 % fuel efficiency reduction in comparison to the all diesel scenario into account. The fuel savings of the wind/solar/diesel scenario amount to 5.1 % or 559,887 liters per year as opposed to the solar/diesel scenario.

6. ECONOMIC AND FINANCIAL ASSESSMENT

6.1. Methodology and assumptions

The economic and financial assessment will focus on quantifying some key indicators. These include the levelized cost of energy (LCOE), the net present value (NPV), the internal rate of return (IRR) and a cash flow projection. LCOE, NPV and IRR are important factors in making investment decisions, as they can be directly compared to indicators of alternative projects. The cash flow is used to assess the break-even point, which denotes the point in time where total costs and revenues are equal. After reaching the break-even point the wind farm starts yielding a net benefit.

In a first step all project costs need to be determined. These are compared to the value of diesel fuel savings which are regarded as revenue. Oil price and therefore diesel fuel price increases are taken into account. As the price projections found in literature assign a specific fuel price to each calendar year, a set timeframe for the wind farm operation needs to be selected.

For the purpose of this study the hypothetical project implementation shall begin in the year 2013. Therefore, the project shall operate from 2014 to 2033, which represents a time span equivalent to the turbine design lifetime. Decommissioning of the wind farm shall commence in 2034. The total project lifetime is therefore 21 years, while the year of implementation is regarded as year zero.

All costs and revenues listed in the economic and financial assessment exclude adjustment for inflation. This is common practice, to allow current values to be compared to future values on an equivalent basis. Additionally, the uncertainty in future inflation rate increases the uncertainty in the financial indicators. Since inflation is disregarded, the discount rate used in this study shall be regarded as the real discount rate, rather than the inflation adjusted nominal discount rate.

In economics the discount rate represents the human preference of attaining an asset in the present rather than in the future. However, weighting the value of a future asset and therefore assigning an appropriate discount rate has been an unresolved controversial issue for many years (Pearce et al., 2003). A study conducted in 2008 found that “In the Pacific, discount rates to analyse resource use have varied between 3 and 12 per cent in the last few years” (Woodruff & Holland, 2008). Therefore, this study will focus on the mid-range value of 7 %, while presenting the sensitivity of using 3 % and 12 % discount rates.

In addition to the financial indicators mentioned above, the economic, environmental and social aspects of wind energy implementation in Tongatapu will be discussed briefly. Here, the focus lies on advantages and disadvantages that cannot be easily quantified in monetary terms. Some recommendations to minimize disadvantages will be given.

6.2. Cost estimates

6.2.1. Project costs

The project costs determined in this chapter will serve as input values for calculating the LCOE, NPV, IRR and cash flow values. All cost items taken into account in this study are listed in Table 18. The table is divided into the capital cost which is due within the implementation phase, the yearly recurring cost, and the renaturation cost which is due at the end of the project lifetime. It is important to note that all cost items exclude possible duties and taxes. As some sources used for reference list their costs in Euros, the exchange rate between Euros (€) and Tonga Pa'anga (TOP) is valued at 1 € = 2.17823 TOP (fxexchangerate.com, 2012).

Table 18 Cost estimate for a 1.1 MW wind farm in Tongatapu

	Rates	Factor		
	Exchange rate € to TOP	2.17823		
No.	**Capital Cost**	**Value [€]**	**Value [TOP]**	**Source**
1	GEV MP ex works, engineering, SCADA	1,351,000	2,942,789	Vergnet proposal
2	Cables and couplings internal, MV delivery substation	91,000	198,219	Vergnet proposal
3	Technical support, commissioning, project management	184,000	400,794	Vergnet proposal
4	Transport to site	134,000	291,883	Vergnet proposal
5	Civil works (between turbines only)	290,070	631,839	Vergnet proposal
6	Assembly	105,000	228,714	Vergnet proposal
7	Operations and maintenance training	13,000	28,317	Vergnet proposal
8	Tools for common maintenance	66,000	143,763	Vergnet proposal
9	Consumables and wear parts for two year operation	22,500	49,010	Vergnet proposal
10	Support to local maintenance team for two years	36,000	78,416	Vergnet proposal
11	New 11 kV feeder (3.5 km at 57,134.15 TOP/km)		199,970	TPL
12	Substation building	5,000	10,891	estimate
13	Access road (between main road and wind farm)	145,035	315,920	estimate
14	Studies (grid, geotechnical, environmental, feasibilty)	50,000	108,912	estimate
	Total capital cost		**5,629,437**	
	Annual recurring cost			
16	Land lease (15 acres at 3000 TOP annualy for 8 acres)		5,625	MECC
17	Operation and Maintenance at 35 € per kW and year	38,500	83,862	(GHD Australia, 2010b)
	Total annual recurring cost		**89,487**	
	Renaturation cost			
18	Technical support, commissioning, project management	184,000	400,794	based on Ver. proposal
19	Transport from site	134,000	291,883	based on Ver. proposal
20	Civil works (between turbines only)	290,070	631,839	based on Ver. proposal
21	Access road (between main road and wind farm)	145,035	315,920	based on Ver. proposal
22	Disassembly	105,000	228,714	based on Ver. proposal
	Total renaturation cost		**1,869,150**	

a. Capital Cost

In order to acquire realistic assumptions concerning the cost per turbine, transport to site and installation, the turbine manufacturer Vergnet was asked to provide a budgetary proposal. The cost item numbers 1 to 10 refer to the figures listed in that document. The budgetary proposal is attached as Appendix 20.

The information communicated to Vergnet states:

"The location of the wind farm will be about 3400 m from the 11kV grid on an approximate elevation of 15 to 20 m above sea level. While the turbines will be located near the coast on the eastern side of the island with good road access, the distance between turbines will be about 160 m."

Based on this information, Vergnet offered to provide the turbines and the remote monitoring system SCADA (no. 1) along with all necessary electrical equipment (no. 2). Upon request Vergnet confirmed that the remote monitoring service, conducted by Vergnet headquarters in France, is included in the budget. Additionally, the proposal contains the following services:

- Commissioning (no. 3)
- Transportation to site (no. 4)
- Civil works including road and trench works (no. 5)
- Assembly (no. 6)

Apart from the services listed above, training to local staff (no. 7) and necessary tools (no. 8) for operation and maintenance (O&M) are provided by the manufacturer. Consumables and wear parts (no. 9) as well as technical assistance to the local staff (no. 10) for the first two years of operation are also included in the budget.

Under services not included Vergnet specifically lists the grid connection. This implies that the cost of a 3400 m long 11 kV feeder from the substation of the wind farm to the distribution grid is not included in the pricing. Therefore, Tonga Power Limited was requested to supply a quotation for building a 1 km 11 kV feeder along an existing road. This document is attached as Appendix 21. The cost of a 1 km feeder is multiplied by a factor of 3.4 to render the cost of the necessary 3.4 km long feeder (no. 11).

Vergnet's proposal states that the cost of the substation (no. 2) only includes the electrical equipment, but not the actual building. Therefore, the estimated building cost is listed separately as item number 12.

Vergnet declared that the road and trench works (no. 5) only cover the distance between turbines, i.e. 480 m. Therefore, the cost to build the necessary access road from the main road to the wind farm is added as a cost item. As this distance stretches only 320 m and does not require trench works, the access road cost (no. 13) is estimated to be half of the cost item "Civil works" (no. 5) quoted by Vergnet.

Before the design of the wind farm can be finalized, a number of studies need to be undertaken to make an informed decision on the project. These studies include a grid study, a geotechnical survey, an extensive environmental impact study as well as a full feasibility study. The cost of these studies heavily depends on whether the necessary skills can be attained in-country, or whether external consultancy needs to be contracted. The combined cost of all studies is estimated in cost item no. 14.

All cost items described above constitute the capital cost which is due prior to operation of the wind farm. In total, the capital cost of the 1.1 MW wind farm in Tongatapu is estimated to be 5,629,437 TOP. This translates to a capital cost of 2,349 € per kW of installed wind power capacity.

b. Annual recurring cost

The Ministry of Environment and Climate Change stated that land lease costs in the area under study are around 2,000 TOP to 3,000 TOP for 8 acres (Sefana, 2012). The annual land lease cost (no. 16) is calculated on the basis of the higher value of 3,000 TOP and a lease area of 15 acres. The lease area is based on the approximation that a 100 m wide stretch of land needs to be cleared around the wind turbines, while the access road required a 10 m wide stretch of land for construction.

Although local staff operation and maintenance (O&M) training cost is included in Vergnet's proposal, the wind farm operator is still required to bear the costs incurred by performing the operation and maintenance. O&M costs listed under cost item number 17 are derived from a 2009 study conducted for Samoa (GHD Australia, 2010b). Here, a 2 MW wind farm is assumed to incur O&M costs of 35 € per kW and year while utilizing the same 275 kW GEV MP C wind turbine as proposed in this study on Tongatapu. The report states that "cost estimates were provided by Vergnet and EPC [the local utility]" (GHD Australia, 2010b). The cost estimate of 35 € per kW and year is therefore considered adequate.

It is important to note that the cost of capital is an annual recurring cost, but was disregarded for the purpose of this study. Tonga Power Limited indicated that a wind power project in Tongatapu may possibly receive grant funding. Unlike a loan, a grant does not incur interest payments. Therefore, the cost of capital is not taken into account, which results in total yearly recurring costs of 89,487 TOP.

c. Renaturation cost

At the end of the project life, i.e. 20 years, the wind farm needs to be dismantled and the land restored to its original state. In Germany, wind energy projects must include this cost into their budget in order to obtain a building permit (BWE, n.d.). Therefore, the same high standard shall be applied in the wind farm under investigation.

According to the German Wind Energy Association, renaturation means disassembling and recycling the wind turbine generators and substation, digging out all the cables in the ground and removing the foundations (BWE, n.d.). For the purpose of this study it shall be assumed that the works required at the end of the project are equivalent to those listed under cost item numbers 3 to 6. The project management (no. 18) would ensure that the turbines are disassembled (no. 22) and then transported to an out-of-country recycling facility (no. 19). Additionally, all civil works carried out during the implementation would be reversed (no. 20) and the access road removed (no. 21). The total renaturation cost amounts to 1,869,150 TOP.

6.2.2. Diesel fuel cost

The diesel fuel cost needs to be assessed because saving this expense warrants the implementation of a wind energy project from a financial perspective. However, forecasting the price of any oil product is subject to a high level of uncertainty because international prices are very volatile. Considering that the Tongatapu wind farm has a lifetime of 20 years, the projections made by this study can only be treated as indicative. Nevertheless, this chapter will attempt to forecast the diesel fuel price in Tongatapu from 2014 to 2033 based on a projection by the World Bank spanning from 2009 to 2020 (World Bank, 2010).

The report analyses how "world crude oil prices might translate into a price of fuel oil used by TPL. Components in the fuel oil price include the price of crude, the premium on that price for the refined fuel oil […] and the cost of shipping and handling to Tonga" (World Bank, 2010). Of the three scenarios listed in that study, the high price projection seems most accurate. Table 19 shows that the price of diesel (denoted fuel oil) was predicted to be 1.97 TOP per liter in the year 2012. According to a press release by the Tongan Ministry of Commerce, Tourism and Labour the wholesale price of diesel for power generation was set at 2.00 TOP per liter for January to February 2012 (MCTL, 2012). The projections made by the high price scenario therefore seem to fit the actual values reasonably well at this point in time.

Table 19 High price projection of diesel fuel (denoted fuel oil) from 2009 to 2020 (World Bank, 2010)

Year	World crude oil (US$/bbl)	World crude oil (US$ per liter)	Singapore gasoil (US$ per liter)	Tongatapu fuel oil (US$ per liter)	Tongatapu fuel oil (T$/liter)
2009	61.00	0.384	0.476	0.658	1.26
2010	78.00	0.491	0.608	0.790	1.52
2011	93.00	0.585	0.725	0.907	1.74
2012	108.00	0.679	0.842	1.024	1.97
2013	122.00	0.767	0.952	1.134	2.18
2014	134.00	0.843	1.045	1.227	2.36
2015	145.00	0.912	1.131	1.313	2.52
2016	148.14	0.932	1.155	1.337	2.57
2017	151.35	0.952	1.180	1.362	2.62
2018	154.63	0.973	1.206	1.388	2.67
2019	157.98	0.994	1.232	1.414	2.72
2020	161.41	1.015	1.259	1.441	2.77

The diesel fuel price projections for the entire period from 2014 to 2033 are listed in Table 20. Figures for the years 2014 to 2020 are based on the values listed in Table 19. Prices from 2021 to 2033 are projections based on the last percentage increase. In spite of being significantly higher in the period from 2010 to 2015, the percentage increase of diesel price decreases to 1.8 % in the year 2020. Therefore, all values in the extended forecast period are calculated using the same annual 1.8 % fuel price increase.

Table 20 Diesel fuel price projections highlighting the relevant forecast period from 2014 to 2033

	Year	Diesel cost [TOP/liter]	Increase from previous year [%]
Values forecasted by World Bank	2009	1.26	
	2010	1.52	20.6
	2011	1.74	14.5
	2012	1.97	13.2
	2013	2.18	10.7
	2014	2.36	8.3
	2015	2.52	6.8
	2016	2.57	2.0
	2017	2.62	1.9
	2018	2.67	1.9
	2019	2.72	1.9
	2020	2.77	1.8
Extended forecast values	2021	2.82	1.8
	2022	2.87	1.8
	2023	2.93	1.8
	2024	2.98	1.8
	2025	3.03	1.8
	2026	3.09	1.8
	2027	3.15	1.8
	2028	3.20	1.8
	2029	3.26	1.8
	2030	3.32	1.8
	2031	3.38	1.8
	2032	3.45	1.8
	2033	3.51	1.8

6.3. Financial indicators

6.3.1. Levelized cost of energy

The levelized cost of energy is that cost at which electricity can be generated over the entire lifetime of a project. This value can be determined independently of the technology used. Therefore, the LCOE allows comparing the electricity cost of different projects, disregarding whether they convert wind, solar or diesel energy. The LCOE is calculated as follows:

$$LCOE = \frac{Total\ Project\ Cost}{Total\ Electricity\ Production}$$

In the case of the Tongatapu wind farm, the total project cost is the sum of the capital cost, the annual recurring cost for twenty years and the renaturation cost. The total electricity production is the sum of all electricity produced during the entire lifetime of the project. Both, costs and electricity production, need to be discounted to their value in the present. In order to take the discount rate into account the LCOE calculation performed in this study shall be defined as noted in Equation 6.12.

$$LCOE = \frac{C_C + \frac{C_R}{(1+r)^n} + \sum_{t=1}^{n} \frac{C_A}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E}{(1+r)^t}} \qquad 6.12$$

$LCOE$ = Levelized cost of energy (TOP/kWh)
C_C = Capital cost (TOP)
C_R = Renaturation cost (TOP)
C_A = Annual recurring cost (TOP)
E = Annual net wind energy production (kWh)
r = Discount rate
n = Project lifetime in years (21 years)

When the discount rate of 7 % is applied to the equation above, the Tongatapu wind farm is expected to produce energy at 24.6 Seniti per kWh which is equivalent to 11.3 €-cent per kWh. The calculation can be viewed in Appendix 22. It is important to point out that LCOE is unaffected by the uncertainty of future diesel fuel cost, but varies greatly with discounting.

Table 21 shows the sensitivity of the Tongatapu wind farm LCOE in relation to the discount rate. When discounting at 12 % the LCOE is 61% higher than when discounting at 3 %. The steep incline in LCOE in relation to the discount rate is characteristic of wind energy, because a large share of the total investment is due at the start of the project.

Table 21 Levelized cost of energy of the Tongatapu wind farm in relation to discount rate

Discount rate [%]	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
LCOE [Seniti/kWh]	19.9	20.9	22.1	23.3	24.6	26.0	27.4	28.9	30.5	32.1

6.3.2. Net present value and break-even point

The net present value of a project is the difference between the sum of all discounted costs and revenues (see Equation 6.13). The NPV determines the value of the investment. While a positive NPV is beneficial, an investment with a negative NPV constitutes a financial loss. Additionally, the NPV can be compared to that of competing projects to decide which choice results in greater returns.

$$NPV = \sum_{t=0}^{n} \frac{(Q_t - C_t)}{(1 + r)^t} \tag{6.13}$$

NPV = Net present value (TOP)
Q_t = Sum of revenues in year t (TOP)
C_t = Sum of costs in year t (TOP)
r = Discount rate
n = Project lifetime in years (21 years)

The difference between the costs and revenues specific to each year is known as cash flow. In order to assess NPV, expected cash flows need to be forecast for a set number of years. Since the Tongatapu wind farm project has a defined duration, the cash flow can be modeled for the entire 21 years of lifetime.

The net present value of the Tongatapu wind farm at the discount rate of 7 % is 9.8 million TOP. However, this value is highly sensitive to the discount rate. Table 22 shows that the NPV at 3 % is almost triple of the NPV at a 12 % discount rate. The cash flow forecast and the detailed calculation of the net present value is listed in Appendix 23.

Table 22 Net present value of the Tongatapu wind farm

Discount rate [%]	**3**	**7**	**12**
NPV [million TOP]	16.2	9.8	5.1

The significant sensitivity is confirmed by plotting the cumulative cash flow shown in Figure 58. Cumulative cash flows of 3 %, 7 % and 12 % discount rates pass the break-even point in the years 2018, 2019 and 2020 respectively. Therefore, the Tongatapu wind farm will pay for itself after 5, 6 or 7 years of operation, depending on the appropriate discount rate.

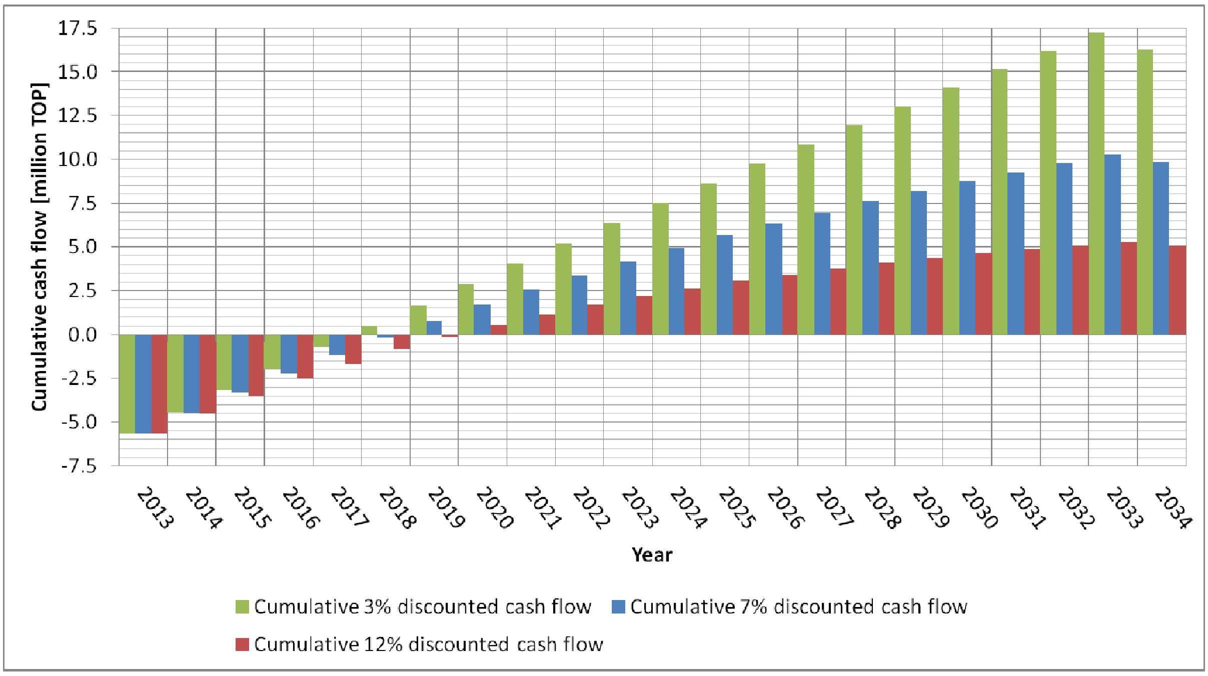


Figure 58 Cumulative cash flow discounted at 3 %, 7 % and 12 %

6.3.3. Internal rate of return

The internal rate of return is used to judge whether an investment is financially viable. When the IRR is larger than the weighted average cost of capital (WACC) then the project is financially viable. When the IRR is smaller than the weighted average cost of capital (WACC) then the project is not financially viable. Since the cost of capital in the grant funding scenario assumed here is zero, the threshold value is 0 %. Additionally, the IRR can be compared to that of competing projects to decide which investment results in higher returns.

Formally, the IRR is equal to that discount rate at which the net present value (NPV) becomes zero. Therefore, the IRR can be calculated by solving for r in Equation 6.14 below.

$$NPV = 0 = \sum_{t=0}^{n} \frac{(Q_t - C_t)}{(1+r)^t} \qquad 6.14$$

NPV = Net present value (TOP)
Q_t = Sum of revenues in year t (TOP)
C_t = Sum of costs in year t (TOP)
r = Discount rate = IRR = Internal rate of return
n = Project lifetime in years (21 years)

According to above equation the internal rate of return is expected to be 24.3 %. Consequently, the Tongatapu wind farm is financially viable up to a discount rate of 24.3 %, at which the NPV reaches zero. The detailed calculation assessing the IRR is listed in Appendix 24.

6.4. Economic implications

Apart from the purely financial perspective provided above, a wind energy project has significant implications in broader economic terms. These effects are not reflected in the financial indicators, because they cannot be easily quantified in monetary terms. Nevertheless, an informed decision on whether to pursue or not to pursue a wind energy project must take non-monetary advantages and disadvantages into account.

A major advantage of implementing wind energy is the reduction of fossil fuel imports. A declining dependency on foreign imports increases energy security in Tonga. This may benefit other sectors such as transport, health or education, because all these activities are dependent on energy. An additional environmental and economic benefit of reduced fossil fuel imports is the reduced risk of fuel spills, since oil contamination is difficult and expensive to clean.

Another important advantage of any renewable energy source that substitutes a fossil fuel source is the mitigation of climate change. Greenhouse gases, mainly carbon dioxide, are released into the atmosphere as exhaust gases when combusting oil products. It is a widely accepted fact that greenhouse gas emissions need to be reduced globally and drastically, in order to curb global warming (IPCC, 2008). Although a system known as the clean development mechanism allows trading emission reduction certificates, the market has essentially collapsed (Harvey, 2012). This uncertain source of revenue was therefore not taken into account within this financial analysis of this study, but the reduction of carbon dioxide emissions still constitute a value on a global scale.

Apart from the indirect advantages mentioned above, the Tongan people will directly benefit from a wind energy project. Employment opportunities will be created, especially within the construction phase of the wind farm. A lower electricity tariff will lighten the burden on all electricity consumers. There may be a possibility that land lease arrangements can be made in a way where a community will benefit from the profit, rather than an individual owner.

It is important to point out, however, that a wind farm project has a number of adverse impacts. Clearing 15 acres of land, pouring concrete foundations and building roads is a significant disruption of the eco-system. Wildlife habitat is destroyed, erosion patterns may be changed and if underground water resources are present, these may be affected.

Wind turbines are shipped in containers together with a large amount of packaging material which must be collected and managed appropriately. Furthermore, the appearance of the wind farm will be a distinct feature of the island, considering that the 71 m tall rotating structures will be visible from far away. Noise emission will disturb the landscape in times of high wind speeds.

Birds and bats may be killed by the rotating blades when hit directly, or by the pressure difference between the front side and the back side of the rotor. This possibility must be assessed carefully, as this risk varies depending on the species present on Tongatapu.

It is important to investigate the negative effects of a wind farm thoroughly in an environmental impact assessment. Experience in Europe and the United States has shown that involving the community and presenting the advantages and disadvantages of the project in a transparent manner is crucial to make an informed decision that benefits the people of Tonga as a whole.

6.5. Summary of the economic and financial assessment

The economic and financial assessment analyzed key financial indicators like the levelized cost of energy, the net present value and the internal rate of return. Additionally, a cash flow projection was used to identify the break-even point. All indicators were shown to be highly sensitive to the discount rate. While a literature review of resource studies from the Pacific concluded that a range of 3 % to 12 % was used in previous assessments, a mid-range discount rate of 7 % was chosen for the purpose of this financial assessment.

A table of costs was compiled based on quotations, literature review and estimates. The capital cost of 5,629,437 TOP translates to a capital cost of 2,349 € per kW or 2,971 USD per kW of installed capacity. Annual recurring costs of 89,487 TOP are due every year for the duration of the 20 years of turbine life. Renaturation costs of 1,869,150 TOP are due in the 21st project year and ensure that the wind farm can be decommissioned appropriately. In line with common practice, inflation is not taken into account in any of these values.

However, diesel fuel price increases are accounted for. It is important to note that any oil product price forecast is subject to a high level of uncertainty. Nevertheless, a projection for the years 2014 to 2033 is based on a forecast provided by the World Bank in 2010. The financial indicators NPV, IRR and the break-even point are therefore valid for a project implementation in 2013 followed by a wind farm operation starting in 2014.

At a 7 % discount rate the LCOE is 24.6 Seniti per kWh. This value is the only financial indicator presented in this study that is not subject to the diesel price projection. The NPV is 9.8 million TOP and the cash flow projection shows that the wind farm will have reached its break-even point after 6 years of operation. The internal rate of return is 24.3 %, meaning that the net present value remains positive up to a discount rate of 24.3 %.

Apart from the purely financial indicators, a decision whether wind power in Tonga should be pursued needs to take into account factors that are not easily quantifiable in monetary terms. While advantages are the reduction of green-house gas emissions, reduced risk of fuel spills, higher energy security, employment opportunities and lower electricity tariffs, developing a wind farm presents a major disruption of the eco-system.

Humans, flora, fauna and the land itself will experience negative effects that must be identified prior to project implementation. Only a transparent presentation of all advantages and disadvantages of implementing the Tongatapu wind farm will allow making an informed decision that will benefit the people of Tonga as a whole.

7. CONCLUSION AND RECOMMENDATIONS

The technical and environmental as well as the economic and financial assessments were based on long-term adjusted wind data that was measured close to the proposed wind farm locations and near wind turbine generator hub height. Therefore, the results presented by this study are sufficiently accurate to justify a decision to further pursue wind energy in Tongatapu.

The configuration of the proposed wind farm is technically feasible. The rated power is below a value where additional energy storage within the Tongatapu electrical grid becomes necessary, yet the wind farm is large enough to make a significant contribution to fuel consumption reduction. The selected wind turbine is commercially available to Tonga, suitable for cyclone prone areas and likely able to meet the turbulence characteristics found on the island.

Financially, a wind farm on Tongatapu presents a viable investment. The net present value and the internal rate of return are positive, and the low levelized cost of electricity represents a fraction of the current electricity tariff. Although a wind energy project has some disadvantages, the overall benefits to the Tongan economy are significant. It is therefore recommended to pursue the implementation of a wind farm by undertaking a full feasibility study.

The following tasks, amongst others, would form part of the full feasibility study:

1. **Validate long-term wind resource**

The average long-term wind speed that was determined within this study was shown to be higher than the average wind speed measured during the wind monitoring campaign. This increase was a result of the higher wind speeds measured at the Fua'amotu International Airport in preceding years. Although this set of reference data was validated as far as possible within the time constraints of this study, additional long-term reference data may be available. These additional datasets may be able to confirm the long-term wind resource assessed within this study.

2. Investigate alternate wind farm locations

The main reason to propose a wind farm close to the Lapaha wind monitoring mast is the high level of accuracy with which wind speeds at a nearby location can be predicted, as opposed to the less accurate prediction made for a farther location. In Europe or the USA, a financier typically demands wind monitoring to be undertaken within 2 km of the centre of the wind farm in order to minimize the risk of production shortfalls due to inaccurate wind modelling.

The wind resource map shows that wind speeds on the north-eastern cape of Tongatapu may be higher than those found at the central-eastern site proposed in this study. When additional measurement data becomes available further north, it may be beneficial to investigate the suitability of a wind farm at both locations. Should the initial assessment encounter a criterion for exclusion at one site, the alternative site can be finalized.

3. Evaluate the availability of land

It is important to secure land through lease agreements not only for the wind farm itself, but also for the construction of transmission lines and access roads. There may be a possibility that land lease arrangements can be made in a way where a community will benefit from the profit, rather than an individual owner. This may facilitate public acceptance to the project.

4. Evaluate uncertainties to quantify P90 value

The annual energy production and therefore the fuel savings and the financial indicators presented in this study are all based on the P50 value, which will be reached with a probability of 50 %. Quantifying uncertainties associated with the wind resource measurement as well as the long-term wind resource adjustment will allow calculation of the P90 annual energy production. Since this value represents the amount of energy that will be produced with a probability of 90 %, basing the financial model on the P90 annual energy production will reduce the financial risk associated with investing into the wind farm. It may therefore be necessary to calculate the P90 value to secure funding for the project.

5. Model the electrical grid

A grid study would assess which upgrades to the electrical grid are required in order to accommodate the wind farm and the associated costs. It is important to ensure that this new generator located far outside of Nuku'alofa, the centre of the electric load, does not breach specified limits on power quality, especially the voltage level. It is important to note that the wind turbine manufacturer has requested access to a grid study before agreeing to ship its wind turbines to Tonga (see Appendix 20).

6. Investigate the need to implement high-speed diesel generators

Due to the intermittent nature of the energy source upon which they rely, the power output from wind turbines and photovoltaic generators can fall from rated power to no power output in under a minute. The proposed wind/solar/diesel system in Tongatapu will therefore need to supply sufficient reserve power, in order to mitigate the effects of sudden cloud cover occurring simultaneously to a sudden drop in wind speed. It is therefore important to investigate whether the existing diesel generators are capable of increasing power output with sufficient speed in order to prevent a blackout. Should this not be the case, implementation of additional high-speed diesel generators may be one solution to cope with sudden drop in wind and solar output. Other energy storage options may also be investigated in close coordination with TPL.

7. Assess the environmental impact

An environmental impact assessment is necessary in order to evaluate the effect a wind farm may have on the environment. The study would need to include the following topics:

- Environmental policy and legislation
- Mitigation measures to decrease the environmental impact
- Monitoring of environmental impacts during the project lifetime
- Assessment of the visual impact on the landscape
- Noise emissions
- Impact on flora and fauna
- Impact on telecommunication systems
- Impact on water resources
- (Construction) waste management

8. **Assess geological and topographical conditions**

The installation of the wind turbine generators is dependent on the geological and the topographical conditions. These will influence the civil engineering steps required and therefore the costs associated with installation of the wind farm. Additionally, the geological study and the topographic survey are important considerations for the wind turbine manufacturer. Vergnet has also requested access to the geological and topographic studies before shipping its wind turbines to Tonga (see Appendix 20).

9. **Confirm wind turbine suitability for turbulence conditions**

At high wind speeds the turbulence conditions measured during the wind monitoring campaign slightly exceeded the threshold values of the IEC 61400-1 ed. 2 Class B specifications (see Chapter 5.2.2). Nevertheless, the small amount of measurements taken at these high wind speeds does not represent a sample large enough to accurately assess the turbulence conditions. It is therefore recommended to confirm the turbulence conditions when the ongoing Lapaha wind monitoring campaign has rendered additional measurements in order to confirm the suitability of the GEV MP C wind turbine generator.

10. **Adapt wind turbine generator locations to additional assessments**

The wind turbine generator locations selected within this study do not reflect all criteria that need to be taken into account for finalizing the layout. Although the selected locations may serve as a baseline, the positions may need to be adapted to the outcome of the following assessments:

- Land availability
- Environmental impacts
- Geological suitability
- Archeological relevance of the construction zone
- Risks associated with bird and bat strike
- Aviation routes
- Microwave radio paths

11. Redesign financial models to include additional quotations rather than estimates

In order to minimize the financial risk associated with the wind farm investment, it is important to base all cost projections on quotations provided by potential contractors rather than estimates. Therefore, the potential costs for a grid study, a geotechnical survey, an environmental impact assessment as well as a full feasibility study need to be evaluated. Additionally, it is important to note that Vergnet's budgetary proposal for supplying and installing the wind turbine generators is based on very limited information. In order to generate a more detailed and accurate proposal, Vergnet will need to be presented with the results of the geological study and the topographical survey. Therefore a revised quotation from the wind turbine manufacturer would also have to be factored into a revised financial calculation.

8. References

(Ackermann, 2005) Ackermann, Thomas (ed). 2005. *Wind Power in Power Systems*. John Wiley & Sons. ISBN 0-470-85508-8. pages 162 - 165.

(AWS Truewind, 2009) AWS Truewind. 2009 (June). *Wind Resource Maps of the Far East Islands*. The World Bank.

(BWE, n.d.) BWE. *Rückbau*. Bundesverband WindEnergie e.V. Accessed 13 September 2012: http://www.wind-energie.de/en/-node/278.

(Cheatham & Zieroth, 2002) Cheatham, C. & Zieroth, G. 2002 (August). *Evaluation of Grid-Connected Wind Electric Power Project Proposals for Rarotonga, Cook Islands*. The Cook Islands Ministry of Energy.

(Clay, 2010) Clay, Bruce. 2010 (28 January). *Lapaha Wind Monitoring Station: Commissioning Details & Operations and Maintenance*. Clay Engineering Ltd. 1. Draft.

(DTU, n.d.) DTU. *WAsP 10 on-line help file*. Technical University of Denmark. Accessed on 24 July 2012: http://-www.wasp.dk/Support/~/media/Risoe_dk/WAsP/-Support/Literature/Documentation/CHM/Wasp10.ashx.

(Ecology Management Aps, 2010) Ecology Management Aps. 2010 (May). *Wind Study and Feasibility Report: Tuvalu Wind Power Development*. The Secretariat of the Pacific Regional Environment Programme (SPREP).

(Eidt, 2012) Eidt, Ernst. 2012 (June). The information was provided in personal consultation with the installer of the photovoltaic generator projects.

(Electric Power Development Company, 2001) Electric Power Development Company. 2001 (April). *Kingdom of Tonga Feasibility Study of Wind Power Plant: Tongatapu Island and Eua Island*.

(EMD, n.d.) EMD. *Theoretical background for noise propagation models*. EMD International A/S. Accessed 03 September 2012: http://help.emd.dk/knowledgebase/content/-ReferenceManual/NoisePropagationModels.pdf.

(EMD, 2012a) EMD. 2012a (May). *WindPRO 2.8 Manual: Energy*. EMD International A/S. Accessed 25 August 2012: http://-help.emd.dk/knowledgebase/content/WindPRO2.8/03-UK_WindPRO2.8_ENERGY.pdf.

(EMD, 2012b) EMD. 2012b (May). *WindPRO 2.8 Manual: Energy - Loss and Uncertainty*. EMD International A/S. Accessed 13 July 2012: http://help.emd.dk/knowledgebase/content/-WindPRO2.8/12-UK_WindPRO2.8_LOSSUNCERTAINTY.pdf.

(EMD, 2012c)	EMD. 2012c (May). *WindPRO 2.8 Manual: Energy - MCP*. EMD International A/S. Accessed 13 July 2012: http://-help.emd.dk/knowledgebase/content/WindPRO2.8/11-UK_WindPRO2.8_MCP.pdf.
(EMD, 2012d)	EMD. 2012d (May). *WindPRO 2.8 Manual: Environment*. EMD International A/S. Accessed 03 September 2012: http://help.emd.dk/knowledgebase/content/windpro2.8/-04-uk_windpro2.8_environment.pdf.
(Enviromet Meteorological Consultants, 1997)	Enviromet Meteorological Consultants. 1997. *South Pacific Wind and Solar Monitoring Project: Final Report*. Forum Secretariat. Vol. D. Appendix IXD.
(EWEA, 2009)	EWEA. 2009. *Wind Energy: The Facts*. The European Wind Energy Association. Accessed on 24 June 2012: http://-www.wind-energy-the-facts.org/documents/download/-Chapter1.pdf.
(Factor 4 Energy Projects GmbH, 2010)	Factor 4 Energy Projects GmbH. 2010 (September). *Wind Data Evaluation after 12 Months - Anabar: Nauru Wind Power Feasibility Study*. The Secretariat of the Pacific Regional Environment Programme (SPREP).
(FEA, n.d.)	FEA. *Annual Report 2010*. Fiji Electricity Authority. Accessed on 27 July 2012: http://www.fea.com.fj/-userfiles/files/ANNUAL%20REPORT%202010.pdf.
(fxexchangerate.com, 2012)	fxexchangerate.com. 2012 (13 September). *Euro(EUR) To Tonga Pa'ang(TOP)*. Accessed on 14 September 2012: http://eur.fxexchangerate.com/top/.
(Garrad Hassan Pacific Pty Ltd, 2007)	Garrad Hassan Pacific Pty Ltd. 2007 (May). *Review of proposed EU Wind Project in Niue*. Garrad Hassan Pacific Pty Ltd. Status: Draft. Issue: C.
(GHD Australia, 2010a)	GHD Australia. 2010a (March). *Final On-Grid Report: Renewable Energy Supply to the Four Island Grids in Tonga*. The World Bank.
(GHD Australia, 2010b)	GHD Australia. 2010b (March). *Upolu (Samoa) Wind Resource Assessment*. UNDP Samoa.
(Google Earth, 2012a)	Google Earth. 2012a. *Devil's Point Wind Farm, Vanuatu. Lat: -17.714660° Long: 168.208521°. DigitalGlobe 2012. Google 2012.* Accessed on: 13 June 2012.
(Google Earth, 2012b)	Google Earth. 2012b. *Eastern coast of Tongatapu Island, Kingdom of Tonga. Lat: -21.189324° Long: -175.093023°. TerraMetrics. Geo Eye 2012.* Accessed on: 31 August 2012.
(Google Earth, 2012c)	Google Earth. 2012c. *Tongatapu Island, Kingdom of Tonga. Lat: -21.143466° Long: -175.169044°. SIO, NOAA, U.S. Navy, GEBCO, LDEO-Columbia, NSF. Google Eye 2012.* Accessed on: 13 June 2012.

(Harvey, 2012)	Harvey, Fiona. 2012 (10 September). *Global carbon trading system has 'essentially collapsed': The UN clean development mechanism, designed to give poor countries access to green technologies, is in dire need of rescue*. The Guardian. Accessed 19 September 2012: http://-www.guardian.co.uk/environment/2012/sep/10/global-carbon-trading-system.
(IEC, 2005)	IEC. 2005. *IEC 61400-12-1: Power performance measurements of electricity producing wind turbines*. Ed. 1. Annex G.
(International Energy Agency, 1999)	International Energy Agency. 1999. *Recommended practices for wind turbine testing: 11. Wind speed measurement and use of cup anemometry*. 1. Edition 1999. Annex XI.
(IPCC, 2008)	IPCC, Intergovernmental Panel on Climate Change. 2008. *Intergovernmental Panel on Climate Change: Fourth Assessment Report: Climate Change 2007: Synthesis Report*. Working Papers.
(IRENA, 2012)	IRENA. 2012 (June). *Renewable Energy Technologies: Cost Analysis Series*. International Renewable Energy Agency. Volume 1: Power Sector. Issue 5/5. Wind Power. Accessed on 31 July 2012: http://www.irena.org/-DocumentDownloads/Publications/-RE_Technologies_Cost_Analysis-WIND_POWER.pdf.
(Kalnay et al., n.d.)	Kalnay et al. *The NCEP/NCAR 40-year reanalysis project*. Bull. Amer. Meteor. Soc. 77, 437-470, 1996. Accessed on 15 June 2012: http://www.esrl.noaa.gov/psd/.
(Karan, 2009)	Karan, Maneesha. 2009 (25 August). 34*m failure*: *FEA admits lack of study in wind farm project. Fiji Times. Accessed on: 13 June 2012: http://www.fijitimes.com/-story.aspx?ref=archive&id=127996.*
(Marshall Day Acoustics, 2005)	Marshall Day Acoustics. 2005 (22 April). *Butoni Wind Farm. Noise Assessment*. Sinclair Knight Merz. Accessed on: 27 September 2012: http://www.skmconsulting.com/-Markets/Europe/Water–Environment/Environmental-Planning–Management/Butoni-Wind-Farm-Project-EIA-Report.aspx.
(MCTL, 2012)	MCTL. 2012 (15 January). *New Petroleum Prices for January – February 2012*. Tongan Ministry of Commerce, Tourism and Labour. Accessed on 15 September 2012: http://www.mctl.gov.to/?p=1290.
(Meridian Energy, n.d.)	Meridian Energy. *Popua Solar Farm*. Accessed on 10 June 2012: http://www.meridianenergy.co.nz/assets/PDF/-What-we-do/Our-projects/Popua-project/Popua-Fact-Sheet-English.pdf.

(National Weather Service, 2002)	National Weather Service. 2002 (5 November). *NCEP/NCAR Reanalysis Project*. National Wheather Service. Accessed on 30 July 2012: http://www.cpc.ncep.noaa.gov/-products/wesley/reanalysis.html.
(NOAA, 2012)	NOAA. 2012 (25 June). *ENSO Cycle: Recent Evolution, Current Status and Predictions*. National Oceanic and Atmospheric Administration. Accessed on 12 July 2012: http://www.cpc.ncep.noaa.gov/products/-analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf.
(Nouvel, 2012)	Nouvel, Patrick. 2012 (July). *The Devil's point Wind Farm: Case study*. UNELCO GDF Suez.
(NRG Systems Inc, 2011)	NRG Systems Inc. 2011 (December). *NRG 60- and 50-meter XHD TallTower™ Installation Manual & Specifications*. NRG Systems Inc. Revision 3. Accessed on 30 July 2012: http://-www.nrgsystems.com/FileLibrary/-fdbaaba20b7f4542b8a9f95aea6aa617/-NRG%2060m%20and%2050m%20XHD%20TallTower%20Installation%20Manual%20-%20Rev%203.0.pdf.
(Otech Engineering Inc, 2009)	Otech Engineering Inc. 2009 (November). *Anemometer Calibration Report*. NRG Systems, Inc. Accessed on 30 July 2012: http://nrgapps.com/calreports/.
(Pearce *et al.*, 2003)	Pearce, D. & Groom, B. & Hepburn, C. & Koundouri, P. 2003. Valuing the future: Recent advances in social discounting. *World Economics*, 4, 121–141.
(Petersen *et al.*, 1997)	Petersen, E.L. & Mortensen, N.G. & Landberg, L. & Højstrup, J. & Frank, H.P. 1997. *Wind Power Meteorology*. Risø National Laboratory, Roskilde. Risø-I-1206(EN). 46 pp. http://www.wasp.dk/Support/~/media/Risoe_dk/WAsP/-Support/Literature/Reports/PDF/-Wind%20Power%20Meteorology.ashx.
(PIEPSAP, 2006)	PIEPSAP. 2006 (March). *Feasibility of Grid-Connected Wind Power for Rarotonga, Cook Islands*. Pacific Islands Energy Policy and Strategic Action Planning. Draft Report.
(PIEPSAP, 2007)	PIEPSAP. 2007 (June). *Market Review for small and Medium Size Wind Turbines*. Pacific Islands Energy Policy and Strategic Action Planning.
(Richert, 2010)	Richert, Clemens. 2010 (July). *GIS-gestützte Analyse des klimatischen Potentials der Windenergie in der Region Freiburg im Breisgau auf der Grundlage von Messungen und Klimasimulationen*. Institut für Physische Geographie der Universität Freiburg.
(Schuster, 2003)	Schuster, Doug. 2003 (28 March). *2x Wind Speed Problem*. Accessed on 27 June 2012: http://rda.ucar.edu/datasets/-ds461.0/docs/2xwind_final.pdf.

(Sefana, 2012) Sefana, ’Ofa. 2012 (August). The information was provided in personal consultation with the Tongan project partner at the Ministry of Environment and Climate Change.

(SPREP, 2006) SPREP. 2006. *2005 Annual Report of the Secretariat of the Pacific Regional Environment Programme*. Accessed on 10 June 2012: http://www.sprep.org/att/publication/-000475_2005AnnualReportSPREP.pdf.

(Svenningsen, n.d.) Svenningsen, Lasse. *WindPRO / Energy. Power Curve Air Density Correction And Other Power Curve Options In WindPRO*. EMD International A/S. Accessed 05 September 2012: http://www.emd.dk/files/windpro/-WindPRO_Power_Curve_Options.pdf.

(TERM, 2010) TERM. 2010 (June). *Tonga Energy Road Map 2010 - 2020: A Ten Year Road Map to Reduce Tonga’s Vulnerability to Oil Price Shocks and to Achieve an Increase in Quality Access to Modern Energy Services in an Environmentally Sustainable Manner*. His Majesty’s Government of the Kingdom of Tonga.

(TERM-IU, 2012) TERM-IU. 2012. *Monthly generation data from January 2007 to October 2011*. Tonga Energy Road Map - Implementation Unit.

(Thøgersen *et al.*, n.d.) Thøgersen, M. L. & Motta, M. & Sørensen, T. & Nielsen, P. *Measure-Correlate-Predict Methods: Case Studes and Software Implementation*. EMD International A/S. Accessed on 12 July 2012: http://www.emd.dk/files/-windpro/Thoegersen_MCP_EWEC_2007.pdf.

(Thøgersen *et al.*, 2011) Thøgersen, M. L. & Sørensen, T. & Nielsen, P. & Grötzner, A. & Chun, S. 2011 (January). *WindPRO / Park: Introduction to Wind Turbine Wake Modelling and Wake Generated Turbulence*. EMD International A/S.

(Thøgersen, 2010a) Thøgersen, Morten Lybech. 2010a (25 June). *WindPRO / MCP: MCP - Measure-Correlate-Predict: An Introduction to the MCP Facilities in WindPRO*. EMD International A/S. Accessed on 27 June 2012: :http://help.emd.dk/-knowledgebase/content/ReferenceManual/MCP.pdf.

(Thøgersen, 2010b) Thøgersen, Morten Lybech. 2010b (10 October). *WindPRO / ONLINE: Remote Sensing Data and Other Data for Download in WindPRO*. EMD International A/S. http://-help.emd.dk/knowledgebase/content/ReferenceManual/-OnlineData.pdf.

(TMS, 2012) TMS. 2012. *NCEP ADP Global Surface Observational Weather Data, October 1999 - continuing. Dataset ds461.0 updated daily*. U.S. National Centers for Environmental Prediction. CISL Data Support Section at the National Center for Atmospheric Research, Boulder, CO, USA. Accessed on 15 June 2012: http://dss.ucar.edu/datasets/-ds461.0/.

(TPL, 2012) TPL. 2012. *Map of Tongatapu's high voltage electricity distribution grid*. Tonga Power Limited.

(Troen *et al.*, 1989) Troen, I. & Petersen, E.L. & Commission of the European Communities & Directorate-General for Science, Research, and Development. 1989. *European Wind Atlas*. Commission of the European Communities, Directorate-General for Science, Research, and Development, Brussels, Belgium.

(U.S. Department of State, 2011) U.S. Department of State. 2011 (October). *Background Note: Tonga*. Accessed on 10 June 2012: http://-www.state.gov/r/pa/ei/bgn/16092.htm.

(van Brink, 2012) van Brink, John. 2012 (September). *Personal e-mail correspondence between the author of this study and John van Brink, Chief Executive Officer of Tonga Power Limited*.

(Vergnet, n.d.) Vergnet. *GEV MP 275 kW*. Vergnet SA.

(Vergnet, 2004) Vergnet. 2004 (11 October). *Design process and third party certifications*. Vergnet SA.

(Vergnet, 2008) Vergnet. 2008 (31 July). *GEV MP. Tilting guyed tubular tower*. Vergnet SA.

(Vergnet, 2009) Vergnet. 2009 (21 January). *GEV MP 32/275L. Power Curve*. Vergnet SA.

(Vergnet Pacific, 2007) Vergnet Pacific, Winergy. 2007 (December). *Wind Mapping Tonga: Tongatapu - 'Eua - Vava'u - Niuatoputapu - Lifuka*. Vergnet Pacific, Winergy.

(Wade, 2005) Wade, Herbert. 2005. *Pacific Regional Energy Assessment 2004: an assessment of key energy issues, barriers to the development of renewable energy to mitigate climate change and capacity development needs to removing the barriers: Tonga National Report*. Vol. 14. Apia, Samoa: Secreteriat of the Pacific Regional Environmental Programme (SPREP).

(Wilkenfeld, 2012) Wilkenfeld, George. 2012. *The costs and benefits of introducing standards and labels for electrical appliances in pacific Island countries*. Secretariat of the Pacific Community. ISBN: 978-982-00-0518-1. page 46.

(Woodruff & Holland, 2008) Woodruff, A. & Holland, P. 2008. *Benefit-cost analysis for improved natural resource decision-making in Pacific Island countries*. SOPAC Secretariat, Suva.

(World Bank, 2010) World Bank. 2010 (January). *Report on the Tonga Electric Supply System: A Load Forecast*. The World Bank.

9. APPENDICES

Appendix 1 Sensor mounting information from Lapaha wind monitoring mast (Clay, 2010)

Logger Channel	**Sensor**	**Model**	**Height (m)**	**Serial No. Calibration Date**	**Notes**
1	Anemometer	40c	30	179500134056 14/11/09	Alignment 22.5˚T slope=0.756 k=0.38m/s
2	Anemometer	40c	30	179500134057 14/11/09	Alignment 202.5˚T Slope=0.756 K=0.37
3	Anemometer	40c	40	179500134144 17/11/09	Alignment 22.5˚T Slope=0.786 K=0.39
13	Anemometer	40c	40	179500134058 14/11/09	Alignment 202.5˚T Slope=0.786 K=0.38
14	Anemometer	40c	50	179500134059 14/11/09	Alignment 22.5˚T Slope=0.756 K=0.39
15	Anemometer	40c	50	179500134145 17/11/09	Alignment 202.5˚T Slope=0.760 K=0.36
7	Wind Vane	200P	37	Part # S1016	Alignment 22.5˚T Slope=0.351 Offset= 22.5
8	Wind Vane	200P	48	Part # S1016	Alignment 22.5 T Slope=0.351 Offset= 22.5
9	Temperature	110	2	Item# 3365	Slope=0.136 Offset=86.38

Appendix 2 Calibration certificate of Lapaha wind monitoring mast's channel 1 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 14 November 2009 — **Revision No: 0**

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

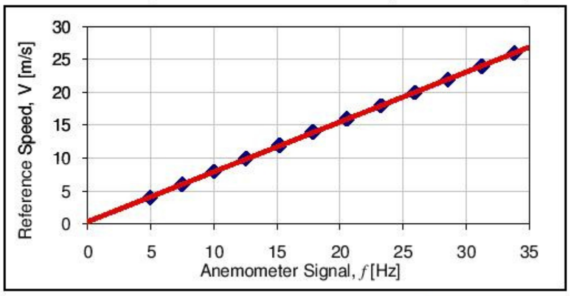
Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134056
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

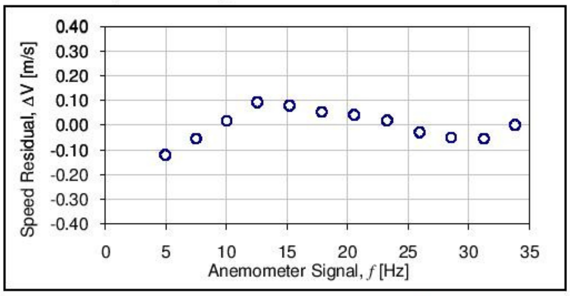
Wind Tunnel Test Facility
Otech Tunnel ID: WT2B
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST traceable)
Amb. Temperature: OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

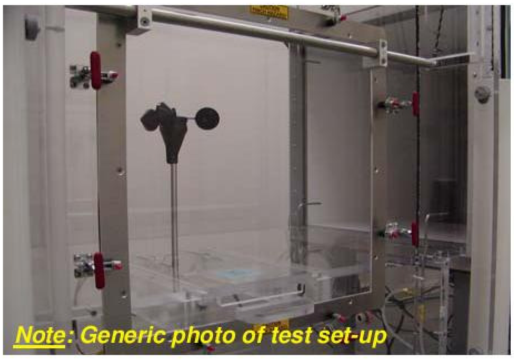
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,793 Pa
Mean Ambient Temperature = 21.3 deg C
Mean Relative Humidity = 30.2% RH
Mean Density = 1.2012 kg/cubic meter





Transfer Function $V\ [m/s] = 0.756\ f\ [Hz] + 0.38$

Test Results: r = 0.99996 std. err. estimate = 0.0663 m/s



Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.996	4.942	-0.120	0.475%
7.968	10.012	0.018	0.467%
11.953	15.199	0.079	0.457%
15.959	20.546	0.041	0.468%
19.968	25.940	-0.028	0.466%
23.954	31.244	-0.054	0.464%
25.960	33.823	0.001	0.473%
21.916	28.544	-0.050	0.468%
17.979	23.247	0.019	0.465%
13.936	17.854	0.054	0.468%
9.958	12.544	0.093	0.460%
5.983	7.481	-0.053	0.697%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

IAS ACCREDITED

References available upon request. Page 1 of 1 179500134056_2009-11-14.pdf

Appendix 3 Calibration certificate of Lapaha wind monitoring mast's channel 2 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 14 November 2009 ***Revision No: 0***

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

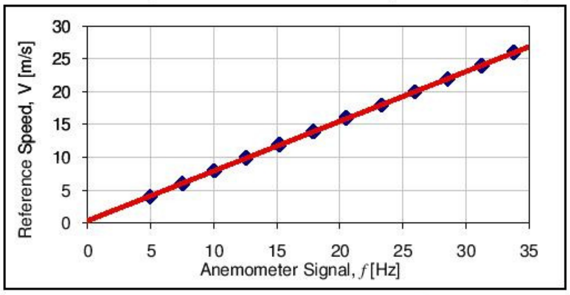
Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134057
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

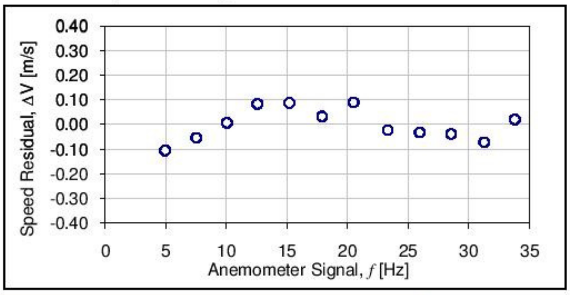
Wind Tunnel Test Facility
Otech Tunnel ID: WT2B
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST traceable)
Amb. Temperature: OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

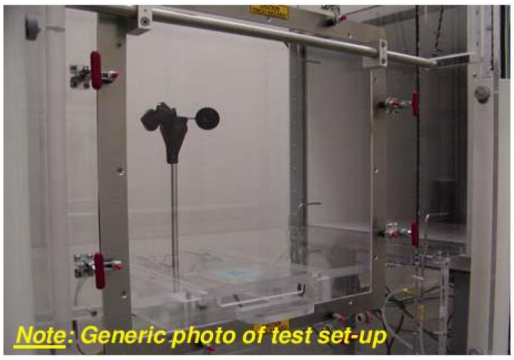
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,808 Pa
Mean Ambient Temperature = 21.4 deg C
Mean Relative Humidity = 30.3% RH
Mean Density = 1.2011 kg/cubic meter





Transfer Function **V [m/s] = 0.756 f [Hz] + 0.37**

Test Results: r = 0.99996 std. err. estimate = 0.0682 m/s



Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.996	4.937	-0.105	0.493%
7.959	10.030	0.007	0.472%
11.946	15.197	0.088	0.474%
15.953	20.493	0.090	0.479%
19.965	25.961	-0.032	0.470%
23.946	31.278	-0.071	0.474%
25.953	33.810	0.021	0.476%
21.917	28.550	-0.038	0.469%
17.974	23.314	-0.022	0.472%
13.931	17.895	0.033	0.467%
9.953	12.566	0.084	0.478%
5.998	7.517	-0.053	0.488%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

IAS ACCREDITED

References available upon request. Page 1 of 1 179500134057_2009-11-14.pdf

Appendix 4 Calibration certificate of Lapaha wind monitoring mast's channel 3 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 17 November 2009 ***Revision No: 0***

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

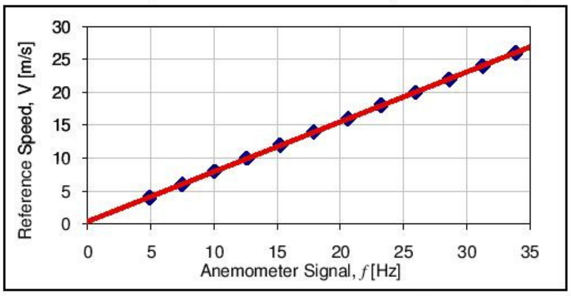
Wind Tunnel Test Facility
Otech Tunnel ID: WT1C
Type: Eiffel (open circuit, suction)
Test Section Size : 0.61 m x 0.61 m x 1.22 m
Manufacturer : Engineering Laboratory Design, Inc.

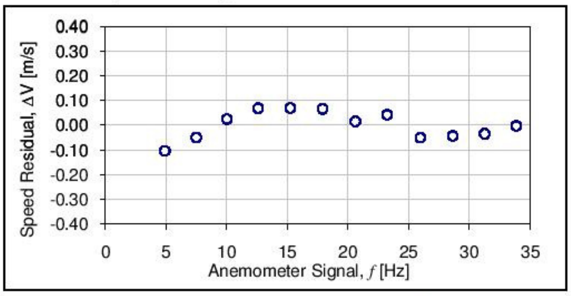
Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure : Setra Model 270 Barometer (NIST traceable)
Amb. Temperature : OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134144
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

Data Acquisition
Hardware : National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software : National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

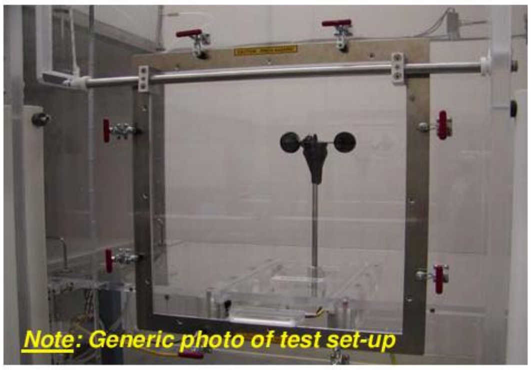
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,582 Pa
Mean Ambient Temperature = 22.5 deg C
Mean Relative Humidity = 27.4% RH
Mean Density = 1.1941 kg/cubic meter





Transfer Function **V [m/s] = 0.756 f [Hz] + 0.39**

Test Results: r = 0.99997 std. err. estimate = 0.0598 m/s



Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.988	4.898	-0.104	0.484%
7.996	10.030	0.025	0.477%
11.979	15.240	0.070	0.472%
15.980	20.605	0.015	0.462%
19.970	25.970	-0.051	0.477%
23.985	31.262	-0.035	0.465%
25.992	33.874	-0.003	0.467%
21.983	28.624	-0.044	0.466%
17.985	23.221	0.042	0.467%
13.989	17.903	0.066	0.466%
9.982	12.599	0.069	0.472%
6.000	7.489	-0.050	0.488%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

IAS ACCREDITED

References available upon request. Page 1 of 1 179500134144_2009-11-17.pdf

Appendix 5 Calibration certificate of Lapaha wind monitoring mast's channel 13 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 14 November 2009 ***Revision No: 0***

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

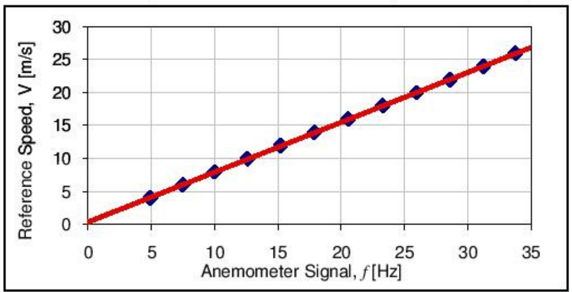
Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134058
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

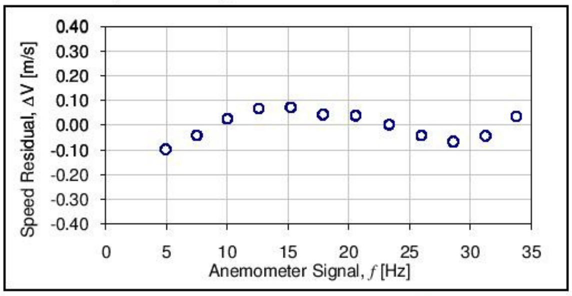
Wind Tunnel Test Facility
Otech Tunnel ID: WT2B
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST traceable)
Amb. Temperature: OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

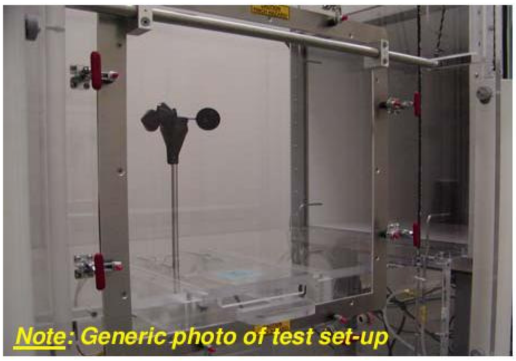
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,813 Pa
Mean Ambient Temperature = 21.4 deg C
Mean Relative Humidity = 30.4% RH
Mean Density = 1.2009 kg/cubic meter





Transfer Function **V [m/s] = 0.756 f [Hz] + 0.38**

Test Results: r = 0.99997 std. err. estimate = 0.0590 m/s



Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.996	4.919	-0.098	0.495%
7.961	10.000	0.027	0.477%
11.950	15.219	0.073	0.473%
15.948	20.552	0.040	0.465%
19.958	25.966	-0.042	0.461%
23.945	31.243	-0.043	0.475%
25.943	33.782	0.036	0.472%
21.921	28.596	-0.067	0.466%
17.990	23.302	0.003	0.465%
13.933	17.880	0.044	0.480%
9.956	12.586	0.068	0.469%
5.987	7.479	-0.042	0.529%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

IAS ACCREDITED

References available upon request. Page 1 of 1 179500134058_2009-11-14.pdf

Appendix 6 Calibration certificate of Lapaha wind monitoring mast's channel 14 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 14 November 2009 ***Revision No: 0***

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

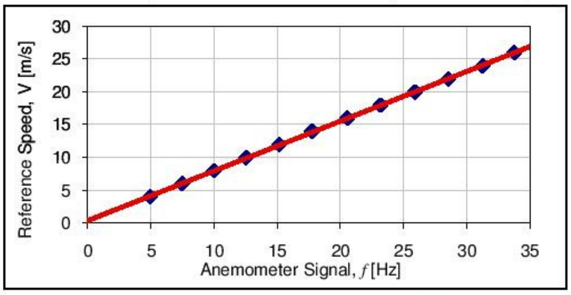
Wind Tunnel Test Facility
Otech Tunnel ID: WT2B
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

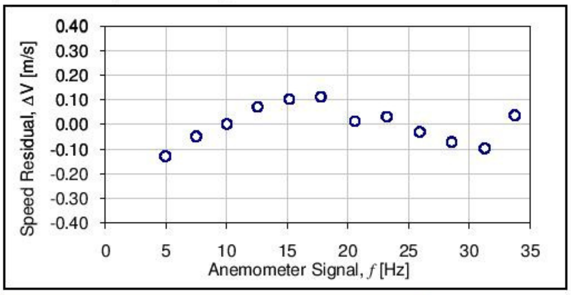
Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST traceable)
Amb. Temperature: OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134059
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

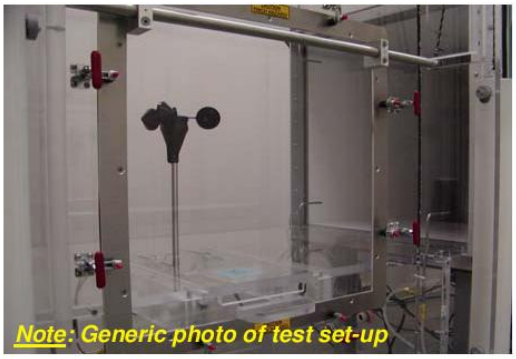
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,814 Pa
Mean Ambient Temperature = 21.5 deg C
Mean Relative Humidity = 30.5% RH
Mean Density = 1.2006 kg/cubic meter





Transfer Function **V [m/s] = 0.756 f [Hz] + 0.39**

Test Results: r = 0.99994 std. err. estimate = 0.0809 m/s


Note: Generic photo of test set-up

Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.995	4.934	-0.129	0.490%
7.964	10.008	0.002	0.471%
11.960	15.159	0.103	0.470%
15.959	20.564	0.014	0.473%
19.961	25.915	-0.030	0.477%
23.953	31.280	-0.096	0.466%
25.966	33.766	0.037	0.465%
21.916	28.554	-0.071	0.485%
17.979	23.211	0.032	0.469%
13.936	17.759	0.113	0.467%
9.951	12.544	0.072	0.474%
5.998	7.477	-0.049	0.484%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

ACCREDITED

References available upon request. Page 1 of 1 179500134059_2009-11-14.pdf

Appendix 7 Calibration certificate of Lapaha wind monitoring mast's channel 15 anemometer (Otech Engineering Inc, 2009)

OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618-7726
Office: (530) 757-2264
http://www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 17 November 2009 ***Revision No: 0***

Customer Information
NRG Systems, Inc.
110 Riggs Road
Hinesburg, VT 05461
USA

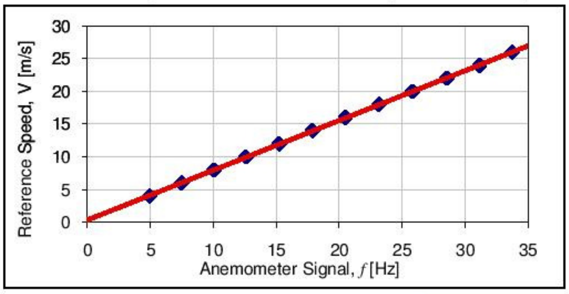
Instrument Under Test (IUT)
Model No: NRG #40
Serial No: 179500134145
Output: AC Sine Wave
Test Procedure: OTECH-CP-001

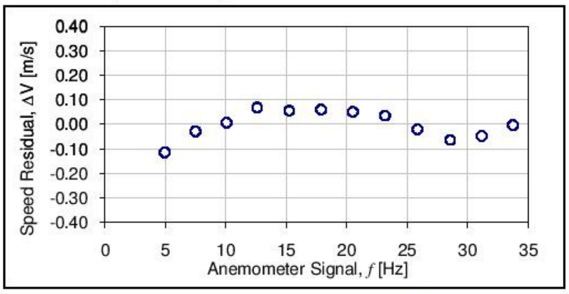
Wind Tunnel Test Facility
Otech Tunnel ID: WT1C
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

Measuring Equipment
Reference Speed: Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST traceable)
Amb. Temperature: OMEGA HX94 SS Probe (NIST traceable)
Relative Humidity: OMEGA HX94 SS Probe (NIST traceable)

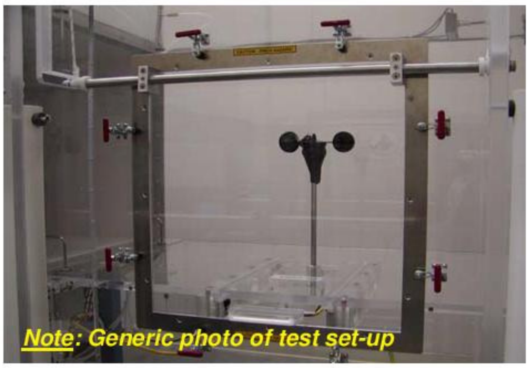
Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101,468 Pa
Mean Ambient Temperature = 22.3 deg C
Mean Relative Humidity = 27.4% RH
Mean Density = 1.1936 kg/cubic meter





Transfer Function **V [m/s] = 0.760 f [Hz] + 0.36**

Test Results: r = 0.99997 std. err. estimate = 0.0599 m/s



Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.998	4.944	-0.114	0.477%
8.001	10.054	0.007	0.467%
11.986	15.237	0.055	0.482%
15.981	20.502	0.051	0.473%
19.971	25.850	-0.020	0.470%
23.977	31.160	-0.048	0.463%
25.993	33.755	-0.003	0.465%
21.986	28.560	-0.064	0.471%
17.985	23.161	0.035	0.475%
13.999	17.881	0.060	0.470%
9.988	12.590	0.069	0.464%
6.009	7.479	-0.029	0.473%

Approved By: Rachael Coquilla, Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

IAS ACCREDITED

References available upon request. Page 1 of 1 179500134145_2009-11-17.pdf

Appendix 8 Data logger and sensor information stored within the data logger

```
SDR     7.1.1

-----Logger Information-----
Model # 4280
Serial #        02874
Hardware Rev.   023-022-000

-----Site Information-----
Site #  0001
Site Desc       Tongatapu
Project Code
Project Desc    Tongatapu
Site Location
Site Elevation  35
Latitude        S 021° 11.359'
Longitude       W 175° 05.581'
Time offset (hrs)       12

-----Sensor Information-----

Channel #       1
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:056
Height  30    m
Scale Factor    0,756
Offset  0,38
Units   m/s

Channel #       2
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:057
Height  30    m
Scale Factor    0,756
Offset  0,37
Units   m/s

Channel #       3
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:144
Height  40    m
Scale Factor    0,756
Offset  0,39
Units   m/s

Channel #       7
Type    3
Description     #200P Wind Vane
Details
Serial Number   SN:s1016
Height  40    m
Scale Factor    0,351
Offset  0
Units   deg

Channel #       8
Type    3
Description     #200P Wind Vane
Details
Serial Number   SN:s1016
Height  50    m
Scale Factor    0,351
Offset  0
Units   deg

Channel #       9
Type    4
Description     NRG #110S Temp  C
Details
Serial Number   SN:3365
Height  2     m
Scale Factor    0,136
Offset  -86,383
Units   C

Channel #       13
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:058
Height  40    m
Scale Factor    0,756
Offset  0,38
Units   m/s

Channel #       14
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:059
Height  50    m
Scale Factor    0,756
Offset  0,39
Units   m/s

Channel #       15
Type    1
Description     NRG #40 Anem. m/s
Details
Serial Number   SN:145
Height  50    m
Scale Factor    0,76
Offset  0,36
Units   m/s
```

Appendix 9 Record of which alterations were performed on the measured wind data

Anemometer data validation				
First record affected	Last record affected	Number of records affected	Action	Reason
22.07.2010 12:00	31.05.2012 11:40	97775	added 12 hours to timestamps	Time set incorrectly upon mast installation
22.07.2010 12:00	23.07.2010 12:20	147	all data deleted	Not all sensors were connected to logger yet
16.05.2011 18:00	16.05.2011 20:10	14	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
27.10.2011 04:40	13.11.2011 17:30	2526	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
02.12.2011 05:00	20.12.2011 04:40	2591	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
19.01.2012 08:10	25.01.2012 00:50	821	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
06.03.2012 01:30	06.03.2012 09:50	51	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
12.03.2012 18:50	31.05.2012 11:50	11479	Ch 15 data deleted	Ch 15 anemometer drops to offset value while all other anemometers record wind speeds
23.03.2012 11:50	16.04.2012 15:00	3476	all data deleted	logger battery was depleted but some short periods of data were recorded
Wind vane data validation				
First record affected	Last record affected	Number of records affected	Action	Reason
07.01.2012 10:30	07.01.2012 10:50	3	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
10.01.2012 15:40	11.01.2012 20:50	176	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
12.01.2012 08:50	12.01.2012 21:20	76	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
13.01.2012 12:00	13.01.2012 16:40	29	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
22.01.2012 17:30	22.01.2012 17:50	3	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
23.01.2012 00:40	23.01.2012 00:40	1	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
28.01.2012 10:00	28.01.2012 19:00	55	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
29.01.2012 05:10	29.01.2012 06:00	6	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
02.02.2012 05:30	02.02.2012 14:30	55	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
04.02.2012 10:50	04.02.2012 18:10	45	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
08.02.2012 23:20	08.02.2012 23:50	4	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
09.02.2012 10:10	09.02.2012 14:40	28	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
21.02.2012 17:00	21.02.2012 19:40	17	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
26.02.2012 16:00	26.02.2012 23:20	45	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
27.02.2012 13:50	27.02.2012 15:30	11	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
05.03.2012 20:40	05.03.2012 21:30	6	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
28.04.2012 05:50	28.04.2012 16:20	64	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
29.04.2012 00:30	29.04.2012 03:30	19	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
29.04.2012 12:00	30.04.2012 18:20	183	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
02.05.2012 17:00	02.05.2012 20:20	21	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
09.05.2012 03:20	09.05.2012 14:50	70	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
13.05.2012 16:10	14.05.2012 10:20	110	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
22.05.2012 03:30	22.05.2012 03:30	1	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
22.05.2012 09:00	22.05.2012 14:00	31	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)
23.05.2012 00:20	31.05.2012 11:50	1222	Ch 7 & CH 8 data deleted	angle difference greater than 30° at wind speed above 3.5 m/s (wind speed of Ch 14)

Appendix 10 Availability of cleaned wind data for all sensors except channel 15

Data		Day of the Month																														
Availibility		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jul-10	89 %																							69	144	144	144	144	144	144	144	144
Aug-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Sep-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Oct-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Nov-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Dec-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Jan-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Feb-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144			
Mar-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Apr-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
May-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Jun-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Jul-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Aug-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Sep-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Oct-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Nov-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Dec-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Jan-12	92 %	144	144	144	144	144	144	141	144	144	94	18	68	115	144	144	144	144	144	144	144	144	141	143	144	144	144	144	89	138	144	144
Feb-12	95 %	144	89	144	99	144	144	144	140	116	144	144	144	144	144	144	144	144	144	144	144	127	144	144	144	144	99	133	144	144		
Mar-12	72 %	144	144	144	144	138	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	72	0	0	0	0	0	0	0	0
Apr-12	42 %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	144	144	144	144	144	144	144	144	144	144	144	80	53	33	
May-12	67 %	144	123	144	144	144	144	144	144	74	144	144	144	97	81	144	144	144	144	144	144	144	112	2								
Total	**94 %**																															

144 measurements per day represent full data recovery, because 24 x 6 ten-minute values are recorded by the data logger.

Appendix 11 Availability of cleaned wind data for channel 15 anemometer

Data		Day of the Month																														
Availibility		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Jul-10	89 %																							69	144	144	144	144	144	144	144	144
Aug-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Sep-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Oct-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Nov-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Dec-10	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Jan-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Feb-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144			
Mar-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Apr-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
May-11	99,7 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	130	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Jun-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Jul-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Aug-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144
Sep-11	100 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Oct-11	85 %	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	28	0	0	0	0
Nov-11	58 %	0	0	0	0	0	0	0	0	0	0	0	0	38	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	144	
Dec-11	42 %	144	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	115	144	144	144	144	144	144	144	144	144	144	144
Jan-12	74 %	144	144	144	144	144	144	141	144	144	94	18	68	115	144	144	144	144	144	49	0	0	0	0	0	138	144	144	89	138	144	144
Feb-12	95 %	144	89	144	99	144	144	144	140	116	144	144	144	144	144	144	144	144	144	144	144	127	144	144	144	144	99	133	144	144		
Mar-12	37 %	144	144	144	144	138	93	144	144	144	144	144	113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apr-12	0 %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
May-12	0 %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0								
Total	**81 %**																															

Appendix 12 Histogram of wind speeds recorded by channel 14 anemometer

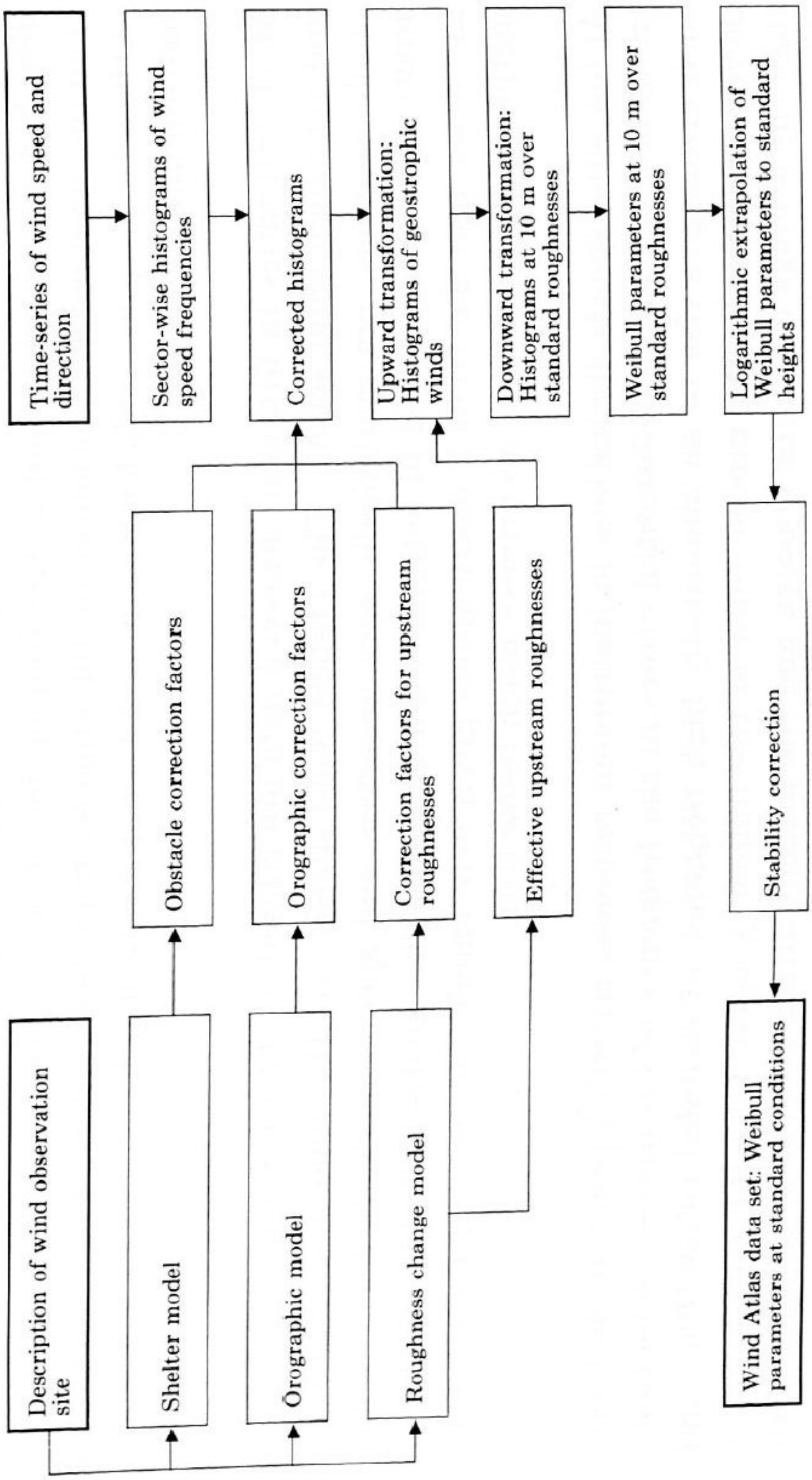
Bin Start [m/s]	Bin End [m/s]	Bin Mean [m/s]	Number of Records
	0,49	**0**	**751**
0,5	1,49	**1**	**1697**
1,5	2,49	**2**	**3716**
2,5	3,49	**3**	**7834**
3,5	4,49	**4**	**11596**
4,5	5,49	**5**	**11879**
5,5	6,49	**6**	**11000**
6,5	7,49	**7**	**10093**
7,5	8,49	**8**	**8890**
8,5	9,49	**9**	**7682**
9,5	10,49	**10**	**5901**
10,5	11,49	**11**	**4933**
11,5	12,49	**12**	**3239**
12,5	13,49	**13**	**1589**
13,5	14,49	**14**	**554**
14,5	15,49	**15**	**243**
15,5	16,49	**16**	**144**
16,5	17,49	**17**	**47**
17,5	18,49	**18**	**23**
18,5	19,49	**19**	**23**
19,5	20,49	**20**	**4**
20,5	21,49	**21**	**8**
21,5	22,49	**22**	**11**
22,5	23,49	**23**	**5**
23,5	24,49	**24**	**10**
24,5	25,49	**25**	**2**
25,5	26,49	**26**	**0**
		Total	91874

Appendix 13 Photos of the eroded shoreline on the eastern side of Tongatapu forming a sudden drop

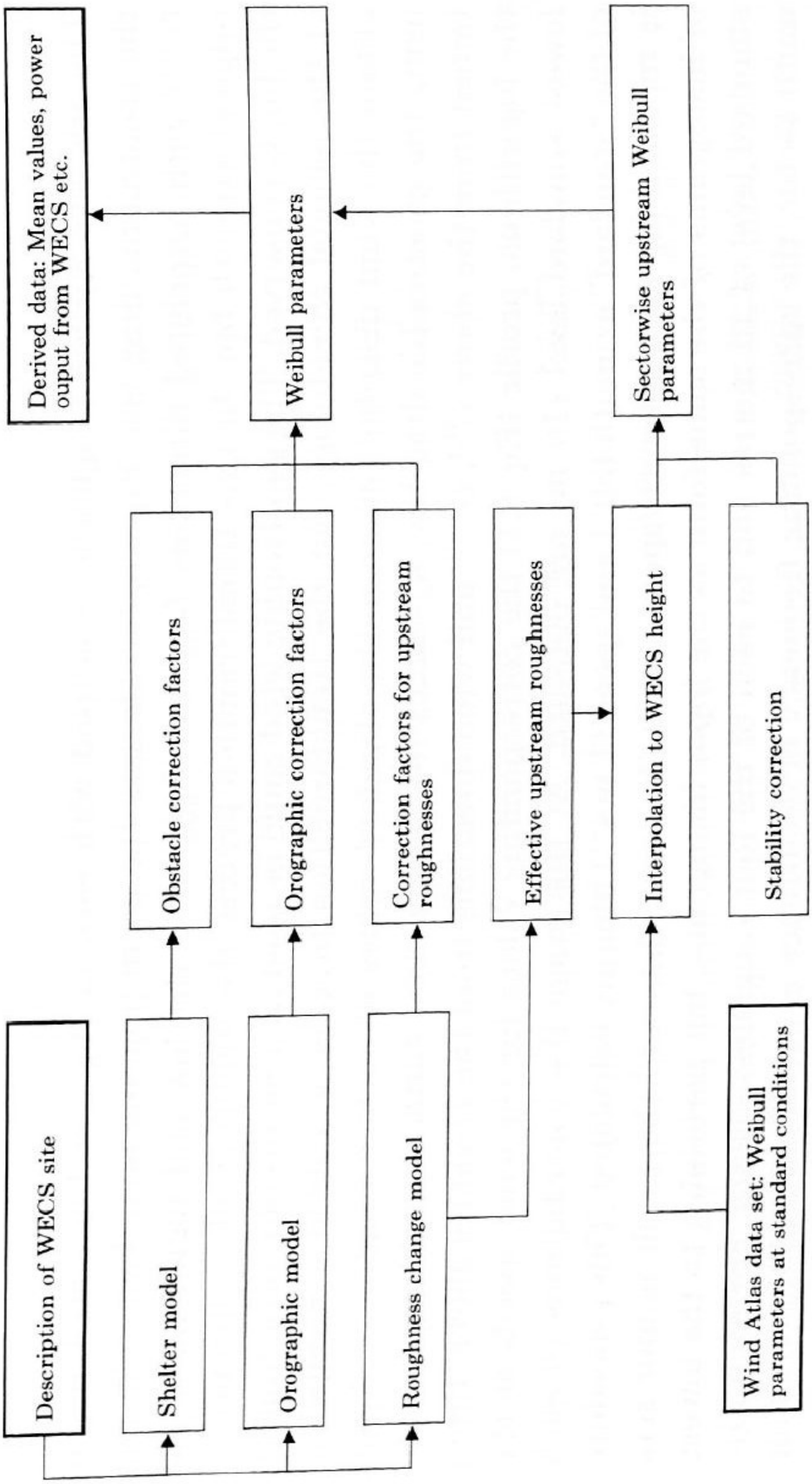
Appendix 14 List of select European land cover types with indicative roughness lengths (DTU, n.d.)

Terrain surface characteristics	Roughness Length [m]
	1.5
tall forest	> 1
city	1.00
forest	0.80
suburbs	0.50
shelter belts	0.30
many trees and/or bushes	0.20
farmland with closed appearance	0.10
farmland with open appearance	0.05
farmland with very few buildings/trees	0.03
airport areas with buildings and trees	0.02
airport runway areas	0.01
mown grass	0.008
bare soil (smooth)	0.005
snow surfaces (smooth)	0.003
sand surfaces (smooth)	0.003
water areas (lakes, fjords, open sea)	0.0

Appendix 15 Flowchart of the WAsP procedure to calculate the generalized regional wind climate (Troen et al., 1989)



Appendix 16 Flowchart of the WAsP procedure to calculate the local wind climate at a point of interest (Troen et al., 1989)



Appendix 17 Overview of key technical figures of the Vergnet 275 kW GEV MP C wind turbine generator (Vergnet, n.d.)

TURBINE CONCEPT

- 2-blade down wind rotor, two-speed generator
- Teetering hub with rubber/metal dampering
- Hydraulic pitch control

• Cut in wind speed - *m/s*	3,5
• Cut out wind speed - *m/s*	20
• Output Voltage & Frequency	400V (3-phase) - 50Hz or 60Hz

• Class (as per IEC 61400-1)	**III**	**II**	**I**
• Hub height - *m*	55/60	55/60	55/60
• Rotor diameter - *m*	32	30	28
• Rotation speed - *rpm (50Hz)*	de 31 à 46	de 31 à 46	de 31 à 46
• Max. wind speed - *m/s*			
Operating position	42,5 to 59,5	42,5 to 59,5	42,5 to 59,5
Lowered position	85	85	85

EXTREME CONDITION PROTECTION

• Corrosion	Marine anti-corrosion protection (C5)
• Generator tightness/insulation	IP55 / Class F
• Hurricane resistance	Lowering system
• Earthquake resistance	Flexible architecture (guyed tower) Multi-pole, shock-absorbent anchors
• Lightning protection	Fully-integrated lightning protection (IEC-61400-24) Lightning arrester on nacelle (IEC 62305/61643-12)
• Operating limits	From -10°C to +50°C

PERFORMANCE DETAILS

• Gearbox	2-stage planetary gearbox
• Generator	2-speed, asynchronous, squirrel cage generator - rated power : 275 kW
• Grid connection	Power factor compensation Electrical cabinet including transformer at tower base
• Emergency and parking brake	Aerodynamic and disc on high speed shaft
• Yaw	Hydraulic active yaw, automatic cable untwisting

MAST

• Type	Guyed : Tubular or Lattice
• Sections	5 x 11,88m
• Material	Galvanized
• Installation	Self-erection via hydraulic winch
• Anchors	Boreholes with steel rods cast in concrete

BLADES

• Material	Twisted vinylester reinforced with fiber glass

CONTROL COMMAND SYSTEM

• Automation control	Industrial automation Siemens through Profibus
• UPS (voltage outage)	56 Ah
• Remote supervision	V-SCADA™ / through RTC, radio, internet...

WEIGHT - DIMENSIONS (CLASS III)

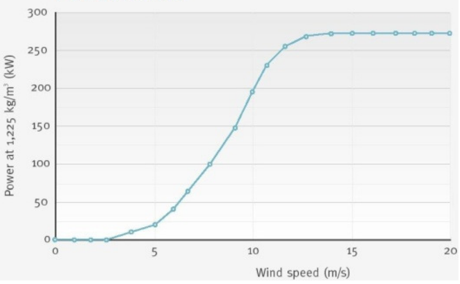
• Nacelle with rotor	7 800 kg
• Wind turbine mast	20 000 kg
• Total packed volume	5x40' containers + blades (1 load)

MANUFACTURERS

• Blades	ACO (VERGNET)
• Blade design	AERODYN
• Gearbox	BONFIGLIOLI
• Generator	ABB

Wind speed (m/s) d=1,225kg.m³	Power (kW) Class III
0	0
1	0
2	0
3	0
4	4,2
5	19,6
6	38,4
7	63,5
8	101,3
9	145,3
10	193,9
11	233,9
12	256,8
13	270,1
14	273,5
15	275
16	275
17	275
18	275
19	275
20	275
21	0
22	0
23	0
24	0
25	0

POWER CURVE



Appendix 18 Power output data of the GEV MP C wind turbine generator at an air density of 1.225 kg/m³ as a function of wind speed (Vergnet, 2009)

Wind speed [m/s]	**Power [kW]**
2,5	0
3,0	0
3,5	0
4,0	3
4,5	10
5,0	18
5,5	27
6,0	36
6,5	47
7,0	58
7,5	78
8,0	98
8,5	119
9,0	141
9,5	164
10,0	189
10,5	215
11,0	243
11,5	262
12,0	272
12,5	275
13,0	275
13,5	275
14,0	275
14,5	275
15,0	275
15,5	275
16,0	275
16,5	275
17,0	275
17,5	275
18,0	275
18,5	275
19,0	275
19,5	275
20,0	275

Appendix 19 Adjusted power output data of the GEV MP C wind turbine generator at an air density of 1.188 kg/m³ as a function of wind speed

Wind Speed [m/s]	Power [kW]
1	0
2	0
3	0
4	2.7
5	17.2
6	34.9
7	56.4
8	94.6
9	136.4
10	182.4
11	233.2
12	267.6
13	275
14	275
15	275
16	275
17	275
18	275
19	275
20	275

Appendix 20 Quotation for four 275 kW GEV MP C wind turbine generators supplied by Vergnet SA

VERGNET WIND TURBINES

VERGNET SA · 1 rue des Chataigniers 45140 ORMES FRANCE

Your contact :	Ron STEENBERGEN
Phone :	+61 (0)2 8003 7449
E-mail :	projectioneering@netspace.net.au

To GIZ

Ormes, August 24, 2012

Dear Sir,

Vergnet, present in 32 countries with 730 turbines and currently installing the biggest wind farm in Africa (120 MW in Ashegoda northern Ethiopia), and sole supplier of cyclone proof wind turbines, would like to thank you for your interest and is pleased to submit you a:

BUDGETARY PROPOSAL FOR

Four (4) GEV MP-C – 275 kW

This offer gives a budgetary estimation for the transport, civil works, installation and commissioning of four (4) GEV MP 275 kW rated power, as well as associated electrical equipment for a wind farm in Tongatapu, Tonga.

Yours sincerely,
Ron STEENBERGEN

1/9

Content of the offer:

1 GENERAL

Considering the initial stage of the project, this document is only a budgetary proposal. The information here within is subject to change following the further discussions between Vergnet (here-after referred to as "Vergnet") and GIZ, carrying out a pre feasibility study for Tonga Government (here-after referred to as "the Client").

2 PROJECT INFORMATION

The following information has been given by the GIZ to Vergnet to locate the wind farm of interest in Tonga island:

"The location of the wind farm will be about 3400 m from the 11kV grid on an approximate elevation of 15 to 20 m above sea level. While the turbines will be located near the coast on the eastern side of the island with good road access, the distance between turbines will be about 160 m."

The hypotheses taken into account for this budgetary proposal are:

	SITE DATA		COMMENTS
Field data	Elevation	15 to 20 m	To be confirmed
	Max ground unevenness	*** No data ***	
	Ambiance	*** No data ***	
Temperature	Min	*** No data ***	To be confirmed.
	Max	*** No data ***	
	Average min	*** No data ***	
	Average max	*** No data ***	
Wind data	Average	6,4m/s at 50m	Information issued from the ENTURA wind report E300243-TR02.
	K Factor	2,28	
	Turbulence level IT15	11,7%	
	Cyclones	yes	
Grid connection	Grid voltage at PCC Frequency	11kV 50 Hz	

No geotechnical and topographical information has been communicated to Vergnet.

3 SCOPE OF SUPPLY

The scope does include:

- 4 Complete nacelle GEV MP C
    - 275 kW rated power
    - 50Hz
- 4 Tubular steel tower
    - hub height 55m
- 4 Rotor blades set, 32m diameter
- Electrical cabinet
    - Wind turbine control,
    - Reactive current compensation device,
    - Power step-up transformer to 11kV
- Electric cables and optical fibre between nacelle and electrical cabinet
- Specific foundation materials: flange, earthing system, anchor rods,
- Consumables for the installation of the turbine,
- Manuals for operation and maintenance,
- SCADA remote control system for wind farm control and monitoring,
- MV cable and fiber optic between the wind turbines,
- MV substation to connect the wind turbines to the grid.

The present offer does not include:

- Specific elements for non standard projects (complementary micro-piles rods and accessories depending on soil specifications/slope...)
- The overhead or underground line to connect the wind farm (from the MV substation) to the main grid.

4 DESCRIPTION OF SERVICES

The following services are proposed:

- Transportation to site,
- Civil works including roads and trench works,
- Assembly,
- Commissioning.

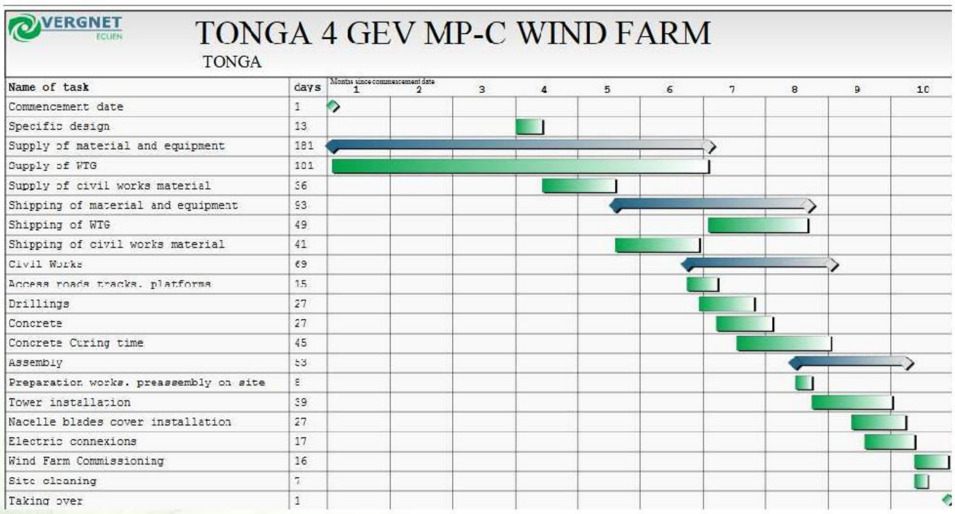
All other items not listed here are the responsibility of the client in particular:

- Site availability, approval from authorities, building permission,
- Geotechnical study,
- Topographic survey,
- Wind Analysis,
- Grid connection study and approval by utility,
- Grid connection

5 INDICATIVE PROJECT SCHEDULE

The machine ex works will be ready for shipment 6 months after T_0. T_0 being conditioned to the reception of the following:

- Down payment and payment guarantees,
- Topological and geotechnical studies,
- Grid connection study.



Name of task	days
Commencement date	1
Specific design	13
Supply of material and equipment	181
Supply of WTG	181
Supply of civil works material	36
Shipping of material and equipment	93
Shipping of WTG	49
Shipping of civil works material	41
Civil Works	69
Access roads tracks, platforms	15
Drillings	27
Concrete	27
Concrete Curing time	45
Assembly	53
Preparation works, preassembly on site	8
Tower installation	39
Nacelle blades cover installation	27
Electric connexions	17
Wind Farm Commissioning	16
Site cleaning	7
Taking over	1

6 O&M SERVICES

Operation and Maintenance are key points to the success of a wind farm in the long term and therefore must be tailored to the client needs.

The O&M services offered shall be considered as the minimum scope to bring Client's organization to be autonomous on operation, preventive maintenance and corrective maintenance of the GEV MP. For that purpose, Vergnet offers:

a) 2 weeks of on-site training on the equipment and positioned after the commissioning of the wind farm
b) Vergnet also offers to assist Client's organization in the performance of the 4 preventive maintenance inspections during the 2 first years (1 week every 6 months).

In detail:

Qty	Service	Comment
1	O&M training on site addressing - Presentation and operation of the GEV MP - Tilting operation training - Preventative maintenance - Operation - Troubleshooting - Wind farm grid connection	Training performed on site for 2 weeks
2	Technical assistance for 2-years preventative - Assistance for 2x semi-annual maintenance (type SA) - Assistance for 1x annual maintenance (type Y1) - Assistance for 1x 2-years maintenance (type Y2)	Delegation of one O&M technical assistants to train Client's team on the job

7 COMMERCIAL OFFER

7.1 Baseline Price

The offered price is:

Designation	Price in Euro
GEV MP Ex Works, engineering, SCADA	1 351 000
Cables and couplings internal, MV delivery substation (equipment, no building)	91 000
TOTAL MATERIAL	**1 442 000**
TECHNICAL SUPPORT AND COMMISSIONING, PROJECT MANAGEMENT	184 000
TRANSPORT TO SITE	134 000
CIVIL WORKS	290 070
ASSEMBLY	105 000
TOTAL SERVICES	**713 070**
TOTAL WIND FARM	**2 155 070**
O&M TRAINING	13 000
Tools for common maintenance	66 000
Consumables and Wear parts for 2 years operation	22 500
VERGNET Support to customer's maintenance team for 2 years	36 000
TOTAL O&M	**137 500**
TOTAL GENERAL PROJECT	**2 292 570**

The above prices are exclusive of all taxes, fees and import duties.

7.2 Payment schedule

The following payment schedule is offered:

Milestone	Payment	% of contract price	Accumulated payments
Order confirmation	Down payment by Bank transfer	35%	35%
Shipment of material	Bank transfer before shipment Or Irrevocable and confirmed L/C payable at sight in a first class bank in Europe at delivery on site	60%	95%
Commissioning	Irrevocable and confirmed L/C payable at sight in a first class bank in Europe	5%	100%

The Letter of Credit shall be put in place at order confirmation.

7.3 Warranties

7.3.1 Material Warranty

The turbines supplied for the project, are covered by a 2-years material warranty. This warranty only covers the parts (except consumables and wearing parts).

7.3.2 Power Curve Warranty

The turbines supplied are covered by a 2-years power curve warranty that warrants the power output against wind velocity.

7.4 General Information

This offer is valid 2 months from date of issue. It cannot be transferred to anyone else than the final.

Vergnet is entitled to withdraw its offer if the site conditions appear to be out of the design range of the turbine or present a significant difficulty.

Appendix 21 Quotation (in TOP) for a 1 km overhead 11 kV feeder supplied by Tonga Power Limited

TONGA POWER LIMITED

Print Date : 29/08/2012
Capex_Key

CAPITAL COST FOR : (Allows 15..) Asset Register (Tongatapu)

EST_00003781 / CUST_003541 / Asset Register (Tongatapu) / 11KV Lines Medium Wooden 1Km / / / / / / Qty of Asset Line is

Tonga Power Limited / SIC / No: 003541 / MA'UFANGA (S.I.C) Ph : contact : /

52k Done

Material	Mat_Qty	Price	Price_Unit	Mat_Cost	
LABOUR - LABOUR	320	25.00	Hr	8,000.00	N
Price - Pole Foundation Weak Mix Concrete (6 to 1)	17	130.44	Each	2,217.40	N
Taxes - Customs Duty 15%	0	1.00	Each	0.00	N
TRANSPORT - BUCKET TRUCK - LARGE EXTEND	48	60.00	Hr	2,880.00	N
TRANSPORT - DIGGER HIRE - SMALL	16	32.50	Hr	520.00	N
TRANSPORT - TRANSPORT SMALL UTE	8	15.00	Hr	120.00	N
TRANSPORT - TRANSPORT TRUCK - LARGE FLAT DECK	8	60.00	Hr	480.00	N
TRANSPORT - TRANSPORT TRUCK - LINE TRUCK	48	60.00	Hr	2,880.00	N
			Sub_Total	17,097.40	
Ampact - Amp Wdg Con Fly - 50cu/Aphis/Gopher Blue - Ampact	6	24.04	Each	144.24	N
Ampact - Amp Wdg Con Fly - Fly Blue - Ampact Wedge	9	22.41	Each	201.69	N
Ampact - Ampact Cartridge - Blue	15	4.88	Each	73.20	N
Binder - Binder Alum PVC 4.2mm	200	2.22	Metre	444.00	N
Bolt - Bolt Galv M12x110	40	1.83	Each	73.20	N
Cable OH - Cable Aluminium Fly 1.4mm Black PVC 062mm	3100	4.44	Metre	13,764.00	N
Crossarm - Crossarm 2.1m 100x75	20	102.68	Each	2,053.60	N
Eye Bolt - Eye Bolt 200xM16 c/w nut Galv	18	16.59	Each	298.62	N
Eye Bolt - Eye Bolt 450xM16 c/w nut Galv	2	21.61	Each	43.22	N
Hardware - Arm Brace Galv 900x30x5 (850mm centres)	40	13.64	Each	545.60	N
Hardware - Crossarm Bracket 100mm Gain Base Galv	20	16.43	Each	328.60	N
Insulator HV - 11kV 1" Pin Leadtop (fits 1130W - 0-0361400-0)	51	14.46	Each	737.46	N
Insulator HV - 11kV Insulator Top 1130W	51	18.43	Each	939.93	N
Insulator HV - Clevis Thimble CAB750 (Alum) Small to Larger Wire	18	19.70	Each	354.60	N
Insulator HV - Insulator Polymer Strain 15kV	18	40.99	Each	737.82	N
Joint - Full Tension Sleeve AL Fly JT5/11/17	10	13.29	Each	132.90	N
Nut - Nut Galv 12mm	36	1.12	Each	40.32	N
Nut - Nut Galv 20mm	46	1.97	Each	90.62	N
Pole HV - Pole Softwood 11m 09KN 225 Min SED H5	14	854.29	Each	11,960.06	N

Print Date : 29/08/2012 28 Page : 1 **Estimate_Parts**

Pole_No **TX_No** Quote prepared By: Samisoni Fatai

Creation_Date 14/11/2008 Approved_By 58,229.67

TONGA POWER LIMITED

Print Date : 29/08/2012

Capex_Key

CAPITAL COST FOR : (Allows 15..) Asset Register (Tongatapu)

EST_00003781 / CUST_003541 / Asset Register (Tongatapu) / 11KV Lines Medium Wooden 1Km / / / / / / Qty of Asset Line is

Tonga Power Limited / SIC / No: 003541 / MA'UFANGA (S.I.C) Ph : contact : /

52k Done

Material	Mat_Qty	Price	Price_Unit	Mat_Cost	
Pole HV - Pole Softwood 11m 12KN 350 Min SED H5	3	1,708.57	Each	5,125.71	N
Preforms - Deadend Fly (PVC) NDE1369 or LTNDE1210	18	10.66	Each	191.88	N
Rod - Threaded Rod Galv M12x1000	9	14.62	Each	131.58	N
Rod - Threaded Rod Galv M20x1000	13	81.98	Each	1,065.74	N
Stay - Deadend Guy grip for 7/12 SGG0765	8	10.84	Each	86.72	N
Stay - Deadman Washer Flat Large Galv M20 100x100x6	2	7.89	Each	15.78	N
Stay - Insulator GY2 IS1 Guy Strain Insulator 400/11kV	2	16.99	Each	33.98	N
Stay - Screw Anchor Galv M32x2.0mx250 Helix	2	168.14	Each	336.28	N
Stay - Stay Guy Wire Galv 7/12	20	4.27	Metre	85.40	N

Sub_Total 40,036.75

MATERIAL, LABOUR and TRANSPORT UNITS	4256	DIRECT COSTS	57,134.15
GROUP UNITS		GROUP COSTS	
		ESTIMATE TOTAL	57,134.15

EXCLUDES CONSUMPTION TAX

Print Date : 29/08/2012 36 Page : 2 Estimate_Parts

Pole_No TX_No Quote prepared By: Samisoni Fatai

Creation_Date 14/11/2008 Approved_By 58,229.67

Appendix 22 Calculation of the levelized cost of energy at a discount rate of 7 %

	Discount rate [%]	7			
Var.	A	B	C	D	E
Source	1)	2)	=A/(1.07)^E	=B/(1.07)^E	
year	**Costs [TOP]**	**Net wind energy production [kWh]**	**Discounted costs [TOP]**	**Discounted wind energy production [kWh]**	**Year number**
2013	- 5,629,437		5,629,437	0	0
2014	- 89,487	2,696,362	83,633	2,519,965	1
2015	- 89,487	2,696,362	78,161	2,355,107	2
2016	- 89,487	2,696,362	73,048	2,201,035	3
2017	- 89,487	2,696,362	68,269	2,057,042	4
2018	- 89,487	2,696,362	63,803	1,922,469	5
2019	- 89,487	2,696,362	59,629	1,796,700	6
2020	- 89,487	2,696,362	55,728	1,679,159	7
2021	- 89,487	2,696,362	52,082	1,569,307	8
2022	- 89,487	2,696,362	48,675	1,466,642	9
2023	- 89,487	2,696,362	45,491	1,370,694	10
2024	- 89,487	2,696,362	42,515	1,281,022	11
2025	- 89,487	2,696,362	39,733	1,197,217	12
2026	- 89,487	2,696,362	37,134	1,118,894	13
2027	- 89,487	2,696,362	34,705	1,045,696	14
2028	- 89,487	2,696,362	32,434	977,286	15
2029	- 89,487	2,696,362	30,312	913,351	16
2030	- 89,487	2,696,362	28,329	853,599	17
2031	- 89,487	2,696,362	26,476	797,756	18
2032	- 89,487	2,696,362	24,744	745,567	19
2033	- 89,487	2,696,362	23,125	696,791	20
2034	- 1,869,150.05		451,424	0	21
		Sum	7,028,886	28,565,300	
		LCOE=	0.246		

1) see Table 18   2) see Table 16

Appendix 23 Net present value based on cash flow forecast at 3 %, 7 % and 12 % discount rate

Var.	A	B	C	D	G	I	J	K
Source	1)	2)	3)	=B*C	=(D-A)/(1.03)^K	=(D-A)/(1.07)^K	=(D-A)/(1.1)^K	
year	**Costs [TOP]**	**Fuel saved [liters]**	**Fuel cost [TOP/liter]**	**Value of fuel saved [TOP]**	**3% Discounted cash flow [TOP]**	**7% Discounted cash flow [TOP]**	**10% Discounted cash flow [TOP]**	**year num.**
2013	5,629,437				- 5,629,437	- 5,629,437	- 5,629,437	0
2014	89,487	559,887	2.36	1,321,333	1,195,967	1,151,258	1,099,862	1
2015	89,487	559,887	2.52	1,410,915	1,245,572	1,154,186	1,053,434	2
2016	89,487	559,887	2.57	1,438,909	1,234,912	1,101,530	960,492	3
2017	89,487	559,887	2.62	1,466,903	1,223,817	1,050,824	875,373	4
2018	89,487	559,887	2.67	1,494,898	1,212,320	1,002,039	797,468	5
2019	89,487	559,887	2.72	1,522,892	1,200,454	955,138	726,208	6
2020	89,487	559,887	2.77	1,550,886	1,188,252	910,086	661,063	7
2021	89,487	559,887	2.82	1,579,395	1,176,147	867,140	601,749	8
2022	89,487	559,887	2.87	1,608,428	1,164,142	826,204	547,746	9
2023	89,487	559,887	2.93	1,637,995	1,152,235	787,183	498,578	10
2024	89,487	559,887	2.98	1,668,105	1,140,427	749,990	453,815	11
2025	89,487	559,887	3.03	1,698,769	1,128,718	714,540	413,063	12
2026	89,487	559,887	3.09	1,729,996	1,117,107	680,753	375,962	13
2027	89,487	559,887	3.15	1,761,798	1,105,594	648,551	342,188	14
2028	89,487	559,887	3.20	1,794,184	1,094,180	617,861	311,442	15
2029	89,487	559,887	3.26	1,827,165	1,082,864	588,612	283,453	16
2030	89,487	559,887	3.32	1,860,753	1,071,645	560,737	257,975	17
2031	89,487	559,887	3.38	1,894,958	1,060,524	534,174	234,783	18
2032	89,487	559,887	3.45	1,929,791	1,049,500	508,860	213,672	19
2033	89,487	559,887	3.51	1,965,265	1,038,573	484,737	194,456	20
2034	1,869,150				- 1,004,760	- 451,424	- 173,008	21
				NPV:	16,248,755	9,813,543	5,100,337	

1) see Table 18   2) see Table 17   3) see Table 20

Appendix 24 Calculation of the internal rate of return

Var.	A	B	C	D	E
Source	1)	2)	3)	= B*C	= D-A
year	**Costs [TOP]**	**Fuel saved [liters]**	**Fuel cost [TOP/liter]**	**Value of fuel saved [TOP]**	**Cash flow [TOP]**
2013	5,629,437				- 5,629,437
2014	89,487	559,887	2.36	1,321,333	1,231,846
2015	89,487	559,887	2.52	1,410,915	1,321,428
2016	89,487	559,887	2.57	1,438,909	1,349,422
2017	89,487	559,887	2.62	1,466,903	1,377,417
2018	89,487	559,887	2.67	1,494,898	1,405,411
2019	89,487	559,887	2.72	1,522,892	1,433,405
2020	89,487	559,887	2.77	1,550,886	1,461,400
2021	89,487	559,887	2.82	1,579,395	1,489,908
2022	89,487	559,887	2.87	1,608,428	1,518,941
2023	89,487	559,887	2.93	1,637,995	1,548,508
2024	89,487	559,887	2.98	1,668,105	1,578,618
2025	89,487	559,887	3.03	1,698,769	1,609,282
2026	89,487	559,887	3.09	1,729,996	1,640,509
2027	89,487	559,887	3.15	1,761,798	1,672,311
2028	89,487	559,887	3.20	1,794,184	1,704,697
2029	89,487	559,887	3.26	1,827,165	1,737,678
2030	89,487	559,887	3.32	1,860,753	1,771,266
2031	89,487	559,887	3.38	1,894,958	1,805,471
2032	89,487	559,887	3.45	1,929,791	1,840,305
2033	89,487	559,887	3.51	1,965,265	1,875,779
2034	1,869,150				- 1,869,150
				IRR:	24.3%

1) see Table 18 2) see Table 17 3) see Table 20